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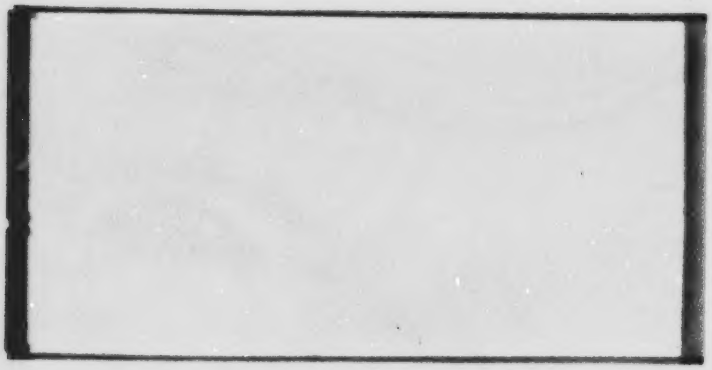

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EFFE[illegible]AND SOCIAL COSTS OF FOSSIL-[illegible]ED EMISSIONS DUE TO ELECTRICAL EXPORTS ON STRUCTURAL MATERIALS

Report No 84-210-K

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ABSTRACT

The effects and economic impact of air pollution, specifically fossil fuel-fired generating station emissions, on structural materials has been reviewed. The annual value of damage to structural materials within Ontario due to Ontario Hydro's fossil-fuel based production of electricity for export was estimated. The cost in 1982 was 0.1 mills/kWh. Forecasts for 1986 and 1989 suggest the value of damage will be 0.05 mills/kWh and 0.07 mills/kWh, respectively. The range of these values is set at a factor of 2 in either direction, one-half the estimated value as the lower limit and twice the value as the upper limit.

job	file	date	report no.
740635-304-591	837.25	January 16, 1985	84-210-K

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EXECUTIVE SUMMARY

This report examines the effects and economic impact of air pollution on structural materials. The value of damage to structural materials within Ontario caused by emissions during Ontario Hydro's fossil-fuel fired generation of electricity for export during the years 1982, 1986 and 1989 is estimated.

Economically significant structural materials susceptible to damage upon exposure to the environment include metals, building stone, paints, textiles, etc. The susceptibility of a material to damage is related to i) the relative reactivity of the material to acidity; ii) the delivery of moisture, acid gases and/or particulates to the material surface, ie, surface exposure which is a function of location, ambient pollution level, and iii) the physical forces resulting from the volume changes associated with the chemical composition of the material. The major emissions from fossil-fuel fired generating stations are SO_2, NO_X and particulates, ie, acid rain precursors. Damage to structural materials from acid rain can be in the form of corrosion of metals, decay of building stone, erosion and discolouration of paints and the weakening and fading of textiles. All of these effects occur to a significant degree as a result of, or in association with, natural environmental conditions, eg, moisture, O_2, CO_2, sunlight, particulate matter, etc. To illustrate, metal corrosion is an electrochemical process requiring moisture for formation of the corrosion cell. The presence of acidic species increases the rate of corrosion. In the case of building stone, water seeps into the material through the pores and provides a transport path for SO_2 deep into the stone. SO_2 reacts with the calcium carbonate of the stone to give gypsum. Gypsum is much more soluble than calcium carbonate and is rapidly washed away. Gypsum also occupies a greater volume of crystallization than calcium carbonate which can cause cracking. Reaction of CO_2, dissolved in water, with the calcium carbonate of the stone can result in stalactite and stalagmite formation. Quantification of the specific contribution of each factor, natural or anthropogenic, to materials' deterioration is difficult.

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A number of methods have been reported in the literature for calculation of the value of air pollutant damage to structural materials. The procedure developed by Salmon (1970) is most widely used. Salmon considered only SO_2 induced damage to structural materials and soiling costs due to particulates. A modified version of Salmon's method was used to estimate the economic impact of fossil-fuel fired production of electricity for export on structural materials within Ontario. The value of damage to galvanized steel (zinc), copper, aluminum, nickel, tin, concrete, brick, stone, paint and glass was estimated. To facilitate calculations, Ontario was divided into five regions: Northern Ontario, Southern Ontario and three 50-km zones around each of Lakeview TGS, Nanticoke TGS and Lambton TGS. The distribution of the materials within the province was assumed to be directly related to the distribution of the population. Damage to structural materials resulting from dry deposition of SO_2 was considered in all zones. Estimates of the damage due to wet deposition of $SO_2+SO_4^{2-}$ were calculated for only the Northern and Southern Ontario zones.

An estimate of the total value of damage to structural materials should also include factors to account for the costs of soiling and the value of damage to cultural properties. Well-documented estimates of these types of damage are not, however, available and no values were assigned.

In 1982, a total of 10 577 GWh of fossil-fuel generated power was exported. The total value of materials damage due to dry deposition of SO_2 and wet deposition of $SO_2+SO_4^{2-}$, resulting from production of the exported power, was $964,000 or 0.1 mills/kWh. Forecasts for 1986 and 1989 suggest 7 713 GWh and 5 585 GWh, respectively, of fossil-fuel generated power will be exported. These exports would result in approximately $388,000 (0.05 mills/kWh) and $395,000 (0.07 mills/kWh), respectively, worth of materials damage. The range of these values is set at a factor of 2 in either direction, one-half the estimated value as the lower limit and twice the value as the upper limit. The estimates of damage are very approximate due to the difficulty in obtaining information about the amount of material actually exposed to air pollution and the rates of corrosion, erosion, etc, in the atmosphere.

TABLE OF CONTENTS

		Page
1.0	INTRODUCTION	1
2.0	OBJECTIVES	2
3.0	DETERIORATION OF STRUCTURAL MATERIALS	2
3.1	Introduction	2
3.2	Environmental Factors	5
3.3	Air Pollutants	6
3.4	Mechanisms of Air Pollutant Materials Damage	7
3.5	Metals	7
3.5.1	Carbon Steel	9
3.5.2	Galvanized Steel (Zinc)	9
3.5.3	Stainless Steel	11
3.5.4	Aluminum	12
3.5.5	Copper	12
3.5.6	Other Metals	13
3.6	Building Stone	14
3.6.1	Limestone and Marble	15
3.6.2	Concrete/Cement	18
3.6.3	Brick	19
3.6.4	Other Stones	19
3.7	Paints	20
3.8	Electrical Components	21
3.9	Textiles/Synthetics	21
3.10	Glass	22
3.11	Cultural Property	22
4.0	SOCIAL COSTS	23
4.1	Methods of Calculation of Social Costs	23
4.1.1	Salmon's Method (1970)	25
4.1.2	Acres' (1980) Adaptation of Salmon's Method	25
4.1.3	Haynie and Spence (1972)	27
4.1.4	Fink, Buttner and Boyd (1971)	28
4.2	Estimation of Social Costs	28
4.2.1	Consumption Volume of Material - Ontario (C)	30
4.2.2	Economic Life of Material (L)	30
4.2.3	Value Added Factor (V)	33
4.2.4	Exposure Factor (E)	33
4.2.5	Interaction Factor (I_r)	34
4.2.6	Population Factor (P_r)	38
4.2.7	Calculation of D_r	38
4.3	Calculation of Social Costs	43

TABLE OF CONTENTS (cont'd)

	Page
5.0 CONCLUSIONS	43
REFERENCES	48
BIBLIOGRAPHY	49
APPENDIX A - Division of Ontario Counties into 8 Regions	50
APPENDIX B - Detailed Calculations of D_r and Assumptions	52
APPENDIX C - SO_2/SO_4^{2-} Concentration and Deposition Data	77
DISTRIBUTION	last page

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EFFECTS AND SOCIAL COSTS OF FOSSIL-FIRED EMISSIONS DUE TO ELECTRICAL EXPORTS ON STRUCTURAL MATERIALS

1.0 INTRODUCTION

Social costs are estimates of the economic damage caused by air pollution to human health, terrestrial ecology, aquatic ecology, exposed structural materials and property value. Ontario Hydro is required, under the National Energy Board Act, to recover the social costs that may be incurred in Canada due to the environmental impact of production of electricity for export, from the price charged to the buyer. This report examines the effects and economic impact of fossil fuel-fired generating station emissions (eg, SO_2, NO_x, particulates and the ensuing acid rain) on structural materials.

The term acid rain is used to describe the deposition of acidic air pollutants or air pollutants which become acidic when they reach the earth's surface and interact with water, soil or plants. There can be three types of acid rain: the first results from local (<50 km) dry deposition of high concentrations of primary emissions, eg, SO_2, particulates; the second, local wet deposition of relatively acidic precipitation, eg, oxidized acids or salts (sulfates, nitrates) and the third, remote (>50 km) dry and wet deposition of acidic pollutants, in relatively mild concentrations, due to long-range transport of emissions. Damage to structural materials from acid rain takes a variety of forms. Damage can appear as corrosion of metals (structural metals, electrical components), decay of building stone, erosion and discolouration of paints, and the weakening and fading of textiles. All of these effects occur to a significant degree as a result of natural environmental conditions, eg, moisture, atmospheric oxygen, carbon dioxide, sunlight, temperature fluctuations, the actions of microorganisms, etc. Quantification of the specific contribution of anthropogenic air pollutants to the damage of structural materials is therefore difficult.

Assessment of the economic damage to structural materials attributable to emissions from coal-fired generating stations requires: (i) an estimate of the rates of deterioration of a material when it is exposed to a polluted atmosphere and the rate of deterioration in the absence of pollutants; (ii) an estimate of the distribution of the materials in the environment; (iii) accurate data on pollutant loadings and the environmental factors coincident with material distribution; (iv) an estimate of the costs associated with the remedial actions necessitated by the damage.

In 1980 Acres Consulting Services Ltd prepared a report on the effects and social costs of air pollution on building materials. The effects of deposition of SO_2 and particulates on steel, zinc, aluminum, copper, nickel, paint, stone, concrete, brick, glass and plastic were examined. This report updates the 1980 Acres' report. The results of a literature review of the effects of air pollution on structural materials (1979-present) are presented in Section 3.0, the methods used to calculate social costs are reviewed in Section 4.0 and estimates of the economic damage due to production of electricity for export, based on 1982 fossil fuel-fired emissions data and projected emissions for the years 1986 and 1989, are given in Section 4.3.

2.0 OBJECTIVES

1. Estimate a range of potential social costs of damage to structural materials including cultural property, due to atmospheric emissions resulting from fossil fuel-fired production of electricity for export. Estimates are to be based on 1982 fossil fuel-fired power plant emissions data and projected emissions for 1986 and 1989.

2. Update Acres' report "Effects of Air Pollution - Building Materials" (1980). Specifically, review (i) the effects of fossil fuel-fired generating station emissions on structural materials and (ii) the methods of assessment of the cost of the damage.

3.0 DETERIORATION OF STRUCTURAL MATERIALS

3.1 Introduction

Economically significant structural materials susceptible to air pollution damage are: metals (eg, galvanized steel, copper), electrical components, building stone (eg, concrete, brick, limestone, marble), paints, textiles/synthetics, glass, etc. Damage incurred by these materials includes corrosion (metals), erosion (building stone, paints), reduced tensile strength (textiles) and fading (paints, textiles). Natural environmental factors and anthropogenic emissions all contribute to the damage, see Table I. The effect of each factor and the reactions involved must be understood in order to distinguish between pollutant-induced damage and deterioration due to natural weathering processes.

The susceptibility of a material to damage is related to (i) the relative reactivity of the material to acidity; (ii) the delivery of moisture and acid gases, and/or particulates to the material surface, ie, surface exposure which is a function of location, geometry, surface texture, ambient pollution level, etc., and (iii) the physical forces resulting from the volume changes associated with changes in the chemical composition of the material, eg, oxidation of iron, conversion of calcite to gypsum (Scholle, 1983). Materials' damage is assessed by measuring the quantitative change in some physical or chemical feature of the material, see Table I.

TABLE I

DAMAGE TO MATERIALS AS A RESULT OF AIR POLLUTION AND NATURAL ENVIRONMENTAL FACTORS (YOCOM AND BAER, 1983)

Materials	Type of Impact	Principal Air Pollutants	Other Environmental Factors	Methods of Measurement
Metals	Corrosion, tarnishing	Sulfur oxides and other acid gases	Moisture, air, salt particulate matter	Weight loss after removal of corrosion products, reduced physical strength, change in surface characteristics
Building Stone	Surface erosion, soiling, black crust formation	Sulfur oxides and other acid gases	Mechanical erosion, particulate matter, moisture, temperature fluctuations, salt, vibration, CO_2, microorganisms	Weight loss of sample, surface reflectivity, measurement of dimensional changes, chemical analysis
Ceramics & Glass	Surface erosion, surface crust formation	Acid gases, especially fluoride-containing	Moisture	Loss in surface reflectivity and light transmission, change in thickness, chemical analysis
Paints & Organic Coatings	Surface erosion discoloration, soiling	Sulfur oxides, hydrogen sulfide	Moisture, sunlight, ozone, particulate matter, mechanical erosion, microorganisms	Weight loss of exposed painted panels, surface reflectivity, thickness loss
Paper	Embrittlement, discoloration	Sulfur oxides	Moisture, physical wear, acidic materials introduced in manufacture	Decreased folding endurance, pH change, molecular weight measurement, tensile strength
Photographic Materials	Microblemishes	Sulfur oxides	Particulate matter, moisture	Visual and microscopic examination

TABLE I (cont'd)

Materials	Type of Impact	Principal Air Pollutants	Other Environmental Factors	Methods of Measurement
Textiles	Reduced tensile strength, soiling	Sulfur and nitrogen oxides	Particulate matter, moisture, light, physical wear, washing	Reduced tensile strength, chemical analysis (eg, molecular weight) surface reflectivity
Textile Dyes	Fading, color change	Nitrogen oxides	Ozone, light, temperature	Reflectance and color value measurements
Leather	Weakening, powdered surface	Sulfur oxides	Physical wear, residual acids introduced in manufacture	Loss in tensile strength, chemical analysis
Rubber	Cracking		Ozone, sunlight, physical wear	Loss in elasticity and strength, measurement of crack frequency and depth

Assessment techniques include measurements of the change in the weight or thickness of a sample, measurement of the change in the surface colour or reflectivity, measurement of loss in tensile strength (Ailor, 1982), chemical analysis or identification of corrosion products (Yocom and Baer, 1983).

In the following, a general review of the environmental factors and air pollutants which contribute to the deterioration of structural materials, the type of damage caused and the mechanisms involved is presented. This is followed by a detailed examination of the effects of specific factors or pollutants on selected structural materials.

3.2 Environmental Factors

The primary environmental factor contributing to the deterioration of structural materials is water. In the absence of water very little atmospheric corrosion or decay would be observed. To illustrate, metal corrosion is an electrochemical process requiring moisture for formation of the corrosion cell. In the case of building stone, eg, limestone, marble, etc, water seeps into the material through the pores and provides a transport path for pollutants (eg, SO_2) deep into the stone. The chemical reactions which ensue can eventually lead to cracking or disintegration of the stone, see Section 3.6. The freezing of water in the fissures of the stone can also cause cracking. Moisture, in the form of precipitation, washes away soluble corrosion/decay products which have accumulated on the material's surface, thereby exposing a fresh surface to further deterioration. Some pollutants require H_2O for formation of the corrosion active species, eg,

$$CO_2 + H_2O \rightarrow H_2CO_3 .$$

The amount of moisture a material is exposed to is determined in part by temperature. The temperature of the air affects the rate of drying, ie, the length of time that a surface remains wet, (Nriagu, 1978). Low surface temperature can lead to condensation on the surface, resulting in corrosion at an accelerated rate, (Stankunas et al, 1983). Temperature also affects the kinetics of the corrosion process. The solubility of oxygen, an oxidizing species in metal corrosion reactions, increases with decreasing temperature, (Nriagu, 1978).

Other environmental factors which contribute to the deterioration of materials are solar radiation, air movement, particles, atmospheric oxygen, atmospheric carbon dioxide (CO_2) and microorganisms, (Yocom and Baer, 1983). Solar radiation causes deterioration of protective organic coatings which can result in exposure of the underlying metal to atmospheric corrosion, (Ailor, 1982). Sunlight affects the tensile strength of textiles and promotes fading of textile dyes. Air movement, which includes wind direction and velocity, can cause temperature and humidity fluctuations, thereby influencing surface-to-air heat transfer and recondensation (Nriagu, 1978). Air movement also affects accumulation of particles on surfaces and the dispersion of air pollutants (Ailor, 1982). Winds can promote abrasion-induced corrosion. The direction from which the air flows

is also important; winds from the sea have a high salt content, winds from industrial areas carry a mix of air pollutants and winds from rural areas are relatively clean.

3.3 Air Pollutants

The major anthropogenic species causing deterioration of structural materials are:

- sulfur oxides (SO_2, SO_3^{2-}, SO_4^{2-})
- nitrogen oxides (NO_2, NO_3^-)
- ammonia (NH_3)
- chloride (Cl^-)
- carbon dioxide (CO_2)
- particulates.

Air pollutants can act synergistically with natural environmental factors or each other to increase damage, (Stankunas et al, 1983).

Sulfur dioxide, nitrogen oxides and particulates are emitted from fossil fuel-fired power plants. Nitrogen-based pollutants are major constituents of automobile exhausts, (Ailor, 1982). Sulfur dioxide and the chloride ion have a wide distribution in the environment and their economic impact in terms of corrosion is high. The primary importance of nitrogen-based pollutants in producing materials damage is in their ability to enter into photochemical reactions involving reactive hydrocarbons to produce 0_3 and other oxidants as secondary products, (Yocom and Grappone, 1976).

Carbon dioxide, CO_2, is a natural component of the atmosphere and has many anthropogenic sources. Automotive combustion is a source of more than 50% of the CO_2 emissions into air. In the presence of water CO_2 is hydrolysed to carbonic acid (H_2CO_3), a very important corrosive agent in the process of weathering, (Winkler, 1970). The solubility of CO_2 in water almost doubles during cooling from about 20°C to near freezing. Cold rain or fog in a heavily polluted atmosphere generally has a very high concentration of H_2CO_3.

Particulates can arise from natural and anthropogenic sources. They accelerate corrosion because of their tendency to absorb moisture and gaseous pollutants. They can also damage surfaces via abrasion. There are three categories of particulates: i) corrosion active particles, eg, mineral salts; ii) particles which in themselves are not corrosion active but which are capable of adsorbing gases (SO_2, H_2O) from the atmosphere, eg, carbonaceous solids such as charcoal; iii) neutral, nonadsorbent particles which cause abrasion, eg, silica (Ailor, 1982). Fly ash produced in high temperature coal combustion has a bimodal size distribution ($\sim$0.02 μm and $\sim$10 μm diameters) with most of the mass occurring in the 1-20 μm diameter size range, (Haynes et al, 1982). Atmospheric sulfates, nitrates

and ammonium compounds, type i particulates, are primarily associated with the 0.05-2 μm diameter size range. Very little acidic or acidifying material is likely to be associated with particles greater than 2 μm. The larger particles (2-100 μm) (type iii) are partly soil-derived, suspended by natural erosion and agricultural practises, and partly the result of the combustion of fossil fuels, eg, carbonaceous solids/soot and silica, (Calvert et al, 1983). Corrosion products and salts from surface contamination (eg, chlorides) greatly influence corrosion rates, principally through the lowering of the critical humidity, the point where corrosion rates begin to accelerate, (Haynie, 1980).

Acidic pollutants may have arrived at a material surface from local pollutant sources or may have been transported many miles from distant sources, (Yocom and Baer, 1983). Source-receptor relationships, eg, local or long-distance sources, must be carefully examined before estimates of damage due to a specific source can be assessed or the effectiveness of any control strategy can be estimated, (Yocom and Baer, 1983).

3.4 Mechanisms of Air Pollutant Materials Damage

A number of mechanisms exist by which air pollutants can cause materials damage. These include:

- direct chemical attack
- indirect chemical attack
- corrosion
- abrasion
- deposition and removal of particulates.

Direct chemical attack occurs when acidic pollutants, deposited on the surface, undergo irreversible reaction with the material. In the case of indirect chemical attack, damage by a pollutant deposited on the material occurs only when the adsorbed species undergoes a chemical change, ie, exposure to moisture generates an acid that attacks the material. Metal corrosion is an electrochemical process requiring a reducing species, the metal, an oxidizing species, usually O_2 or H^+, and an electrolyte, a film of moisture on the surface. Abrasion involves solid particles travelling at high velocities. Particulates can also discolour materials and efforts to clean the surface may result in damage.

3.5 Metals

Corrosion of metals is an electrochemical process. Moisture is required for formation of the electrochemical cell. The rate of corrosion is governed by the diffusion of moisture and oxygen to the metal surface. The presence of acidic species increases the rate of reaction. The anode reaction in every corrosion cell is oxidation of the metal:

$$M \rightarrow M^{n+} + ne^- \quad (1)$$

eg, $$Zn \rightarrow Zn^{2+} + 2e^- \quad (2)$$

$$Al \rightarrow Al^{3+} + 3e^- \quad (3)$$

Several cathodic reactions are frequently encountered:

Hydrogen evolution	$2H^+ + 2e^- \rightarrow H_2$	(4)
Oxygen reduction (acidic solutions)	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	(5)
Oxygen reduction (neutral or basic conditions)	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	(6)
Metal ion reduction	$M^{3+} + e^- \rightarrow M^{2+}$	(7)
Metal deposition	$M^+ + e^- \rightarrow M$	(8)

Hydrogen evolution is a common cathode reaction in acidic media, equation 4. Reduction of oxygen is also common since any aqueous solution in contact with air is capable of producing this reaction. Reduction of O_2 in acidic media yields H_2O, equation 5, while under basic or neutral conditions OH^- is formed, equation 6. During corrosion more than one oxidation and one reduction reaction can occur. Since the anodic and cathodic reactions are mutually dependent, it is possible to reduce corrosion by reducing the rate of either reaction. To illustrate, iron will not corrode in O_2-free water because no cathodic reaction is possible.

The relative length of time a metal surface is wet is the single most important factor affecting metal corrosion. The corrosion rates of a variety of metals increase rapidly if the relative humidity rises above certain threshold values. The threshold relative humidity is known as the critical humidity. The critical humidity is not, however, a constant value but is dependent upon both the hygroscopicity of the corrosion products and the hygroscopicity of the contaminant species which may be present on a metal surface. For most metals the critical humidity varies between 60-80%. At humidities greater than 80%, all SO_2 molecules hitting a rusty surface are adsorbed, (Mattson, 1982).

Corrosion damage to metals is related to their position in the electromotive series, (Mattson, 1982). The susceptibility of a metal to corrosion as a result of acidic deposition is determined by the solubility of the metal's salts and the stability of the metal oxide coating that forms when the metal is exposed to the atmosphere, (Mattson, 1982). Metals most likely to be affected by acidic rain are those whose corrosion resistance depends upon a layer of carbonates, oxides or sulfates, eg, Zn and Cu. In addition to zinc (galvanized steel) and copper, other structural metals susceptible to corrosion include iron and aluminum. The atmospheric corrosion of each metal is discussed in the following.

3.5.1 Carbon Steel

Steels are iron-carbon alloys in which the carbon content is in the approximate range 0-2% by weight. As the carbon content of steel is increased the steel becomes stronger but less ductile. Carbon steel consists basically of iron and carbon. Carbon steels can be alloyed with various inorganic elements in order to improve their mechanical or corrosion resistance.

Unalloyed carbon steel when exposed to the atmosphere forms a protective layer of oxides, or rust. This layer generally consists of two regions: (1) an inner region next to the steel/rust interface consisting primarily of dense, amorphous FeOOH with some crystalline Fe_3O_4; and (2) an outer region consisting of loose, crystalline α-FeOOH and γ-FeOOH. Formation of these layers of rust is initiated on the steel surface under hygroscopic deposits or it may occur at surface inclusions such as MnS which dissolve when the surface becomes wet. The transport of reactants through the layers of rust determines the rate of corrosion. The layer of rust almost completely absorbs any SO_2 reaching the surface, and catalyzes its oxidation to SO_4^{2-}. This leads to the formation of sulfate agglomerates or so-called sulfate nests. When the surface becomes wet, the sulfate nests, in combination with the surrounding area, form corrosion cells, see Figure 1. The anodes are located inside the sulfate nests and the surrounding area acts as the cathode. The reactions expected to take place in the corrosion cells include:

anode: $$Fe \rightarrow Fe^{2+} + 2e^- \quad (9)$$

cathode: $$1/2\ O_2 + H_2O + 2e^- \rightarrow 2OH^- \quad (10)$$

$$Fe^{3+} + e^- \rightarrow Fe^{2+} \quad (11)$$

rust layer: $$2Fe^{2+} + 3\ H_2O + 1/2\ O_2 \rightarrow 2FeOOH + 4H^+ \quad (12)$$

The sulfate nest gradually becomes enclosed within a semipermeable membrane of hydroxide, FeOOH, formed as a result of hydrolysis of the iron ions. The electric current in the corrosion cell causes migration of SO_4^{2-} ions into the nest, stabilizing the existence of the cell.

3.5.2 Galvanized Steel (Zinc)

Galvanized steel is carbon steel coated with zinc. Zinc as a coating on carbon steel is anodic with respect to steel. When the two metal surfaces are in contact with electrolyte (moisture), ie, at a scratch or cut surface, an electrochemical cell is formed. The zinc is oxidized preferentially and the flow of electrons to steel protects it from oxidation, (Haynie, 1980). Therefore, the zinc coating is sacrificed to protect the steel.

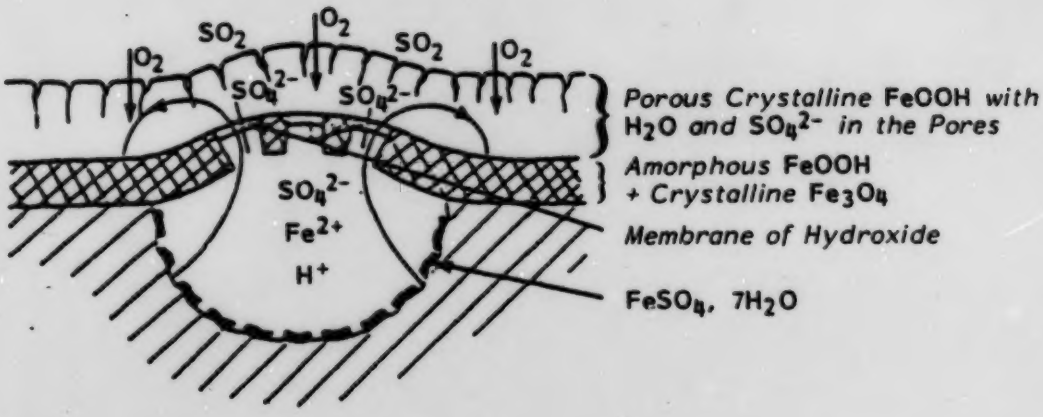


FIGURE 1

SKETCH OF CORROSION CELL AT SULFATE NEST ON STEEL
(Mattson, 1982)

The thickness of the layer of zinc on most galvanized steel products is 25 μm. A full 25 μm of corrosion must occur before damage to the substrate becomes significant, (Stankunas et al, 1983). The life of zinc galvanizing is greater than 25 years in clean, rural areas. In many severely polluted urban or industrial areas the corrosion rate has increased to 5 μm/y, resulting in a lifetime of less than 5 years, (Nriagu, 1978).

Protection of zinc in the outdoor environment depends largely on the formation of a carbonate coating, equations 13 and 14, (Salmon, 1970).

$$Zn + 1/2\ O_2 + H_2O \rightarrow Zn(OH)_2 \qquad (13)$$

$$Zn(OH)_2 + CO_2 \rightarrow ZnCO_3 + H_2O \qquad (14)$$

When the zinc surface comes into contact with acid rain, the carbonate coating dissolves. SO_2 induced corrosion proceeds two times faster than that for the equivalent amount of deposited sulfuric acid aerosol.

NO_2 (0.05 or 0.5 ppm) does not have any effect on the corrosion of zinc, (Acidification Today and Tomorrow, 1982). Corrosion can be accelerated by accumulations of fly ash rich in iron. Dry H_2S (50% RH) and moisture saturated H_2S cause only limited corrosion of zinc because of formation of a coherent protective sulfide film (Nriagu, 1978).

The amount of bare galvanized steel directly exposed to the exterior environment has decreased sharply in recent years. This is due primarily to the development of coatings which adhere to galvanized metal to provide a long lasting surface treatment (Stankunas et al, 1983). Coil-coated galvanized steel is relatively unaffected by SO_2 and has a lifetime of 70 years (Ailor, 1982). Damage to galvanized steel is therefore now thought to be much less important than previously believed (Stankunas, et al, 1983). The dominant uses of bare galvanized steel are transmission towers (power and telephone lines), chainlink fences, wires (barbed wire, cables), and sheet metal (roofing, siding and guttering). Galvanized steel is used predominantly in commercial and industrial buildings. The greatest direct use by consumers is farm buildings.

3.5.3 Stainless Steel

Stainless steel is an alloy of carbon steel and chromium (at least 10.5%). Chromium renders the steel resistant to corrosion in polluted atmospheric environments. If any corrosion does occur it generally consists of slight discolouration or shallow pitting. The mechanical properties of most stainless steel alloys are unaffected by prolonged atmospheric exposure in a mild industrial or a maritime environment (Ailor, 1982).

3.5.4 Aluminum

Aluminum and its alloys form a thin, dense oxide film immediately upon exposure to the atmosphere. The stability of the oxide coating extends down to pH 2.5 (Yocom and Grappone, 1976). This oxide film is responsible for the relatively high resistance of aluminum to weathering and corrosion. The original metallic lustre does, however, gradually disappear with exposure to the atmosphere; the rate of change and the appearance depend upon climatic conditions and the degree of man-made pollution. Chloride ions can penetrate the oxide layer and initiate pit formation. In the presence of moisture an electrochemical cell is created. In the pit, aluminum is oxidized to Al^{3+} (anode reaction). The cathode reactions involve reduction of H^+ or O_2 and take place inside the pit or outside, close to the mouth of the pit, respectively. Hydrolysis of the Al^{3+} ions produces acid conditions within the pit and a cap of $Al(OH)_3$ is formed over the mouth of the pit. The corrosion products eventually block operation of the pit. The formation of corrosion products produces a thin gray rust on the shiny metal surface. If the atmosphere contains much soot, it will be adsorbed by the corrosion products and give the patina a dark colour.

The presence of very high levels of SO_2 causes discolouration, some pitting and surface roughening due to the formation of corrosion products. At very high concentrations of SO_2 and 72% RH, $Al_2(SO_4)_3 \cdot 18H_2O$, a white powder is formed (Yocom and Grappone, 1976).

The low penetration rate and shallow pitting do not generally influence the mechanical properties of aluminum. Low strength aluminum alloys used in homes and architectural applications have the highest resistance to weathering (Mattson, 1982).

3.5.5 Copper

The most visible effect of atmospheric corrosion of copper and its alloys is the change in colour of the metal surface as a result of formation of corrosion products (Ailor, 1982). No general reduction in mechanical properties occurs. The fine crust of corrosion products, known as a patina, can vary in colour from black to green depending upon the age of the coating and its chemical composition. The dark coating consists primarily of copper (I) oxide, while greenish tones originate from basic copper sulfate, chloride, nitrate or carbonate salts. At SO_2 concentrations less than 1% and relative humidities greater than 75% the dominant product of reaction of SO_2 with copper is copper sulfate. Copper sulfate is therefore the main component of the patina found in urban and industrial atmospheres. Reactions involved in the formation of the patina include (Nriagu, 1978):

$$Cu + H_2O \rightarrow CuO + 2H^+ + 2e^- \quad (15)$$

$$Cu + 2H_2O \rightarrow Cu(OH)_2 + 2H^+ + 2e^- \quad (16)$$

$$SO_2 + O_2 + 2e^- \rightarrow SO_4^{2-} \quad (17)$$

$$Cu(OH)_2 + SO_4^{2-} \rightarrow CuSO_4 + 2OH^- \quad (18)$$

The patina may also contain small amounts of iron compounds, siliciferous dust and soot. In rural areas the patina is made up of copper nitrate, copper carbonate or copper sulfate (Ailor, 1982). Copper chloride predominates in maritime environments. The corrosion rate is generally low and decreases somewhat after the first few years of exposure indicating the formation of a slightly protective layer of corrosion products.

Green staining of stonework adjacent to copper roofs is often observed. This is the result of dissolution of traces of copper (salt) in water as it flows down from the roof. The dissolved copper is adsorbed on the stonework.

Hydrogen sulfide causes tarnishing of copper due to the formation of CuS. CuS can affect the resistance across electrical contacts (Ailor, 1982).

Brass is an alloy of copper and zinc. Brasses with a high zinc content can suffer dezincification when exposed to outdoor atmospheres. A correlation between stress corrosion cracking of nickel-brass springs, relative humidity and nitrate concentration has been observed (Ailor, 1982).

3.5.6 Other Metals

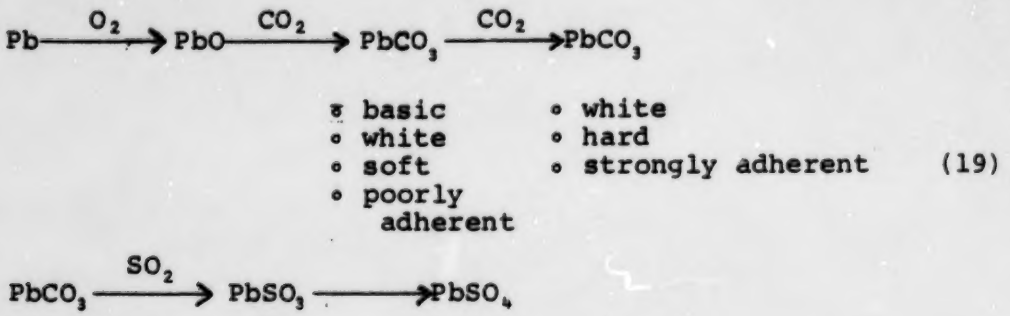
Magnesium

Magnesium is one of the lightest commercial metals and when alloyed shows good strength. It is used in the construction of items such as aircraft, missiles, shipping containers, luggage, ladders, automobile engine parts, trucks, etc. Magnesium is generally anodic to most other metals and is used as a sacrificial anode for cathodic protection (cf, zinc or carbon-steel, and dry-cell batteries). Magnesium exhibits good resistance to ordinary inland atmospheres due to the formation of a protective oxide film. The protection, however, breaks down in air contaminated with salt and/or most acids, and protective measures, eg, coatings, "chrome pickling," are required. Attack of airborne corrodents usually results in a reduction in the tensile strength of the exposed material. Severe corrosion related failures have been encountered (Ailor, 1982).

Lead

Lead coatings are applied to metals to combine the advantages of the desirable mechanical properties of the underlying metal and the corrosion resistance properties of lead (Ailor, 1982). Lead and its alloys are used as piping, sheet linings, solder (Pb-Sn), type metals, storage batteries, radiation shields, cable sheath, terneplate (steel coated with Pb-Sn alloy), bearings, roofing and ammunition (Fontana and Greene, 1978).

Lead, when exposed to the atmosphere, forms a patina the composition of which is dependent upon the constituents of the atmosphere, equation 19.



The time scale for the series of reactions shown in equation 19 depends upon the particular atmosphere and the time of wetness during early exposure. Free access of air is essential for formation of the coating. A shortage of CO_2 inhibits formation of the intermediate basic lead carbonate. A fully protective corrosion product is generally in evidence within six months. The protective property of the coating is due to the insolubility of the corrosion products. Lead is more resistant to atmospheric corrosion than other metals, eg, cadmium, copper, magnesium, nickel or zinc, because its SO_3^{2-}, SO_4^{2-} and Cl^- salts are only slightly water soluble (Nriagu, 1978).

Tin and Tin Plate

The primary use of tin is coating other metals, primarily steel to make the "tin" can. Tin should be cathodic to steel, but the potential reverses in most sealed cans containing food products and the tin acts as a sacrificial coating thus protecting the steel. Tin shows good resistance to atmospheric corrosion, dilute mineral acids in the absence of air and many organic acids, but is corroded by strong mineral acids (Fontana and Greene, 1978).

Tin is often alloyed with lead and used as a solder. High humidity enhances reaction of Sn-Pb solders with low concentrations of Cl_2 to give $PbCl_2$ and $SnCl_2$.

Nickel

Nickel is resistant to many corrosives, especially alkaline solutions, and generally shows good resistance to neutral and slightly acid solutions. It is not resistant to strongly oxidizing solutions, eg, nitric acid and ammonia solutions. The corrosion rate of nickel has been found to increase sharply with the concentration of sulfur compounds in the atmosphere. US studies suggest a corrosion rate of 0.25 μm/y in rural/marine atmospheres, 1.8 μm/y in urban/industrial areas and 6 μm/y in heavily polluted areas.

3.6 Building Stone

Common masonry materials can be separated into two classes, natural and artificial. Natural building stones include limestone, marble,

sandstone, basalt and granites. Brick, concrete, mortar and terra cotta are artificial materials. Both types of stones are composed primarily of carbonates and silicates (SiO_4^{4-}, $AlSi_8O_8^-$). Calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are common constituents of limestone and marble, and interstitial cementing agents in sandstone. Limestones, sandstones and marbles also contain variable quantities of clay minerals, eg, kaolinite ($Al_2Si_2O_5(OH)_4$). Complex silicates are formed in the process of fabrication of concrete and terra cotta.

Stones containing a high proportion of calcium carbonate are particularly vulnerable to damage from acidic deposition. The two most important physical properties affecting the weathering and deterioration of stone are porosity and pore structure. Porosity governs the transport of H_2O and chemically active gases into stone and thereby determines the decay rate. The cracks and pores in rocks form a continuous, interconnected network and rock under natural conditions is usually saturated with fluid.

The effects of natural environmental factors and anthropogenic air pollutants on specific masonry materials are considered in the following sections.

3.6.1 Limestone and Marble

Limestone is of sedimentary origin and composed primarily of calcite ($CaCO_3$) or dolomite, the double carbonate of calcium and magnesium, ($CaMg(CO_3)_2$). It can also contain varying amounts of other material, eg, quartz sand or clay, mixed in with the carbonate minerals. Almost all limestones have relatively high intrinsic microcrack and bedding permeability. Marble is a crystalline rock composed predominantly of calcite, dolomite or serpentine ($Mg_3Si_2O_7 \cdot 2H_2O$). Geologically, marble is formed by the recrystallization of a limestone or dolomite under relatively high heat and pressure.

Deterioration of limestone and marble as a result of exposure to the atmosphere can occur in a number of ways:

(1) penetration of water into the stone;
(2) reaction of CO_2/H_2O with the stone;
(3) reaction of SO_2 with the stone;
(4) oxidation of iron reinforcing bars.

When water which has penetrated into the fissures of the stone freezes, the expansion which occurs causes mechanical stress and results in cracking. (The volume occupied by water at 0°C increases by 9% when it turns to ice). Sound, massive rocks are much more susceptible to deterioration by freezing than are unsound rocks having small pores.

Carbon dioxide, dissolved in water, reacts with calcium carbonate ($CaCO_3$) to give $Ca(HCO_3)_2$, equation 20.

$$CaCO_3\,(s) + CO_2\,(g) \xrightarrow{H_2O} Ca(HCO_3)_2\,(aq) \qquad (20)$$

As the water evaporates, $CaCO_3$ is precipitated on the stone's surface or stalactites or stalagmites may form. During prolonged rainfall, $Ca(HCO_3)_2$ may be completely drained from the stone's surface (Gauri, 1980). The reaction with CO_2 is confined to the period of wetness of the structure.

Reaction of SO_2 with the calcium carbonate of the stone can occur under wet or dry conditions. In the presence of H_2O, the following reactions occur, equations 21 and 22:

$$CaCO_3 \xrightarrow{SO_2/H_2O} CaSO_3 . 1/2H_2O + CO_2 \xrightarrow{O_2/H_2O} CaSO_4 . 2H_2O \qquad (21)$$

$$CaCO_3 \xrightarrow{SO_2/H_2O} CaSO_3 . 2H_2O + CO_2 \qquad (22)$$

Gaseous SO_2 reacts with $CaCO_3$ to give $CaSO_4$, equations 23 and 24 (Yocom and Baer, 1983).

$$CaCO_3 + SO_2 \rightarrow CaSO_3 + CO_2 \qquad (23)$$

$$CaSO_3 + 1/2O_2 \rightarrow CaSO_4 \qquad (24)$$

Damage due to dry pollutant deposition is exemplified by the reaction between sulfates, in particulate matter or in the form of ammonium sulfate, and calcium carbonate, equations 25 and 26.

$$(NH_4)_2SO_4 + CaCO_3 \rightarrow CaSO_4 + (NH_4)_2CO_3 \qquad (25)$$

$$(NH_4)HSO_4 + CaCO_3 \rightarrow CaSO_4 + NH_4HCO_3 \qquad (26)$$

Anhydrous $CaSO_4$ is hydrated to form gypsum. Gypsum, $CaSO_4 . 2H_2O$, is approximately thirty times more soluble in water than calcium carbonate, and is rapidly washed away by rain (Scholle, 1983; Stankunas et al, 1983). Conversion of carbonates to sulfates also results in an increase in the volume of crystallization of 1.5 to 4.2 times (Nriagu, 1978). This can cause mechanical stress within the stone and result in cracking. It is difficult to establish the rate of attack by SO_2 since it overlaps with CO_2 attack (Gauri, 1980). On the surface of marble, impurities such as Fe_2O_3 and colloidal deposits can catalyze oxidation of SO_2 to SO_3.

Gypsum forms crusts on protected surfaces where no rain can wash the material. Incorporation of ambient soot yields a black, impermeable crust. The crust does not protect the surface but accelerates decay because it prevents evaporation of moisture. SO_2 is transported further into the stone along the water film, and the crust continues to grow inward, resulting in greater damage to the stone. The thickness of the gypsum crust depends upon the quality of the marble, the way it was cut and sculptured, the degree of protection of the surface from moisture (rain) and the microclimate (Ailor, 1982).

Acidified water corrodes around the grain boundaries of the stone leaving the grains unsupported so that they eventually dissociate from the main structure. As the layers of surface fall off, relatively clean surfaces are exposed to acidic deposition.

Studies of weathered surfaces of limestone blocks from buildings 100-500 years old reveal that weathered surfaces can absorb as much SO_2 as a fresh surface cut from the same block (Ailor, 1982). Maximum concentrations of sulfur were not found at the surface of the block but some distance below it. Surface reactivity is believed to be maintained by the continuous removal of soluble $CaSO_4$ by rainfall.

The gray veins in limestone, sandstone and marble are due to the aggregation of clay minerals, ie, hydrated silicates of aluminum. These minerals absorb water and will adsorb or exchange ions from circulating waters. The resulting increase in volume occupied by the clay minerals makes them a potential source of stone decay. Adsorbed sulfates in clay minerals are sites for the nucleation of gypsum.

The majority of stone fractures are coincident with the dark clay mineral bands, especially where these bands terminate at mortar joints between blocks (ie, marble). Mortar joints are designed to drain water that may accumulate in the masonry. They are therefore often the site of excess water. During dry weather, water is able to evaporate quickly at the surface leaving the mortar dry. Use of polymeric compounds as mortar can be very damaging. Polymeric compounds are impervious to the movement of water, and water which has infiltrated the masonry can be trapped in the stone for prolonged periods of time (Gauri, 1980).

Treatment of monuments (limestones, marbles) with organic or inorganic protective coatings can also lead to accelerated deterioration. These coatings act as do layers of gypsum/soot and polymeric matter and prevent evaporation of moisture.

Corrosion of metal bars, usually iron, used for anchoring blocks of stone with each other and with the structural framework can also be a source of damage to stone. Oxidation of the iron bars produces FeOOH which occupies a greater volume than the parent iron. The increase in volume can generate stresses sufficient to disintegrate the stone (Gauri, 1980). Oxidation of the bars occurs as a result of the penetration of O_2, H_2O and acidic species through the stone. Increases in the concentration of ions in the H_2O film increase the oxidation rate of the iron bars in the masonry.

The magnitude of attack by NO_2/HNO_3 is unknown (Gauri, 1980). $Ca(NO_3)_2$ from reaction of nitrate with calcium carbonate is not seen, either it does not form, or it is rapidly removed from the surface as a result of its higher solubility (Gauri, 1980). Studies of the corrosion of sandstone in Venice revealed that the concentration of nitrate in the outermost layer of the stone surface was only 1/100th of the sulfate concentrations measured (Acidification Today and Tomorrow, 1982).

Biological weathering of limestone and marble (and sandstone) is also possible. Some bacteria on the surface of the stone can draw SO_2 from the atmosphere. The microbe's metabolic system converts the gas to H_2SO_4 which it uses as a digestive fluid. The digestive fluid attacks the calcium carbonate in the stone, liberating CO_2 the microbe nutrient, and $CaSO_4$ is produced as a by-product (Memorandum of Intent, 1981).

3.6.2 Concrete/Cement

Concrete consists of sand and gravel bonded together with cement. Cement is a mixture of calcium silicates. The composition of Portland cement, a typical cement is shown below:

$3CaO.SiO_2$	50%
$2CaO.SiO_2$	25%
$3CaO.Al_2O_3$	10%
$4CaO.Al_2O_3.Fe_2O_3$	10%
other oxides	10%

Gypsum is added to Portland cement to expedite the setting of concrete. Many concrete structures therefore exfoliate due to the crystallization of gypsum in subsurface regions (Gauri, 1980).

Cement is readily attacked by sulfate. In the presence of sulfate, hydrated calcium aluminate and/or the calcium hydroxide component of the hardened cement paste are converted to ettringate (calcium sulfoaluminate hydrate) and gypsum ($CaSO_4.2H_2O$) (Nriagu, 1978). These sulfates are soluble and can be easily washed away by precipitation. Deterioration of concrete by reaction with sulfates is particularly marked in subaqueous environments and in moist cells. Cements used in dams, bridge piers and culverts therefore require a special formulation to insure sulfate resistance when exposed to concentrations in excess of 200 ppm SO_2 in H_2O. Sulfate resistant cements have a high alumina content, they are predominantly $CaO.Al_2O_3$ (Nriagu, 1978). In acidic media dissolution (or removal) of $Ca(OH)_2$ and hydrolysis of the various cement components to give a residue consisting of silica gel, aluminum hydroxide gel and ferrioxide gel can occur. These reactions substantially reduce the strength and rocklike character of the cement and concrete (Nriagu, 1978).

Deterioration of reinforced concrete, ie, concrete containing steel reinforcing bars, is due primarily to the rusting (oxidation) of the bars. Rusting results in expansion of the bars which can cause cracking of the concrete (Yocom and Baer, 1983). The chloride ion has been found to be a major contributor to the corrosion of reinforced concrete (Yocom and Baer, 1983).

3.6.3 Brick

Brick is a durable, versatile and attractive building material. Its composition varies from clay (containing quartz, feldspar, calcite) to fireclays to kaolin and sericite schist. With exposure to the atmosphere, shifts in colours and accumulation of surface dirt can occur. In severe cases, crumbling occurs. The extent of deterioration is dependent upon the severity of environmental exposure, structural design and the chemical and physical properties of the brick. Properly fired bricks have unusual resistance to attack by chemical agents. However, in the case of inadequate firing even water will react slightly with the glassy constituents of a highly porous brick resulting in a decrease in strength of the unit. Acidic solutions can accelerate such an attack, eg, H_2SO_4 solutions increase dissolution of brick approximately 10 fold. Maximum dissolution of the brick is usually about 1%. The resulting salts are a source of staining and efflorescence on the masonry structure. The damage to the appearance is, however, generally greater than that to mechanical strength.

With exposure to moisture, particles of lime or gypsum within the clay raw material can expand. The expansion can be sufficient to disintegrate masonry units or crack and destroy the walls. Saturation of building brick with salt solution can produce failure similar to that resulting from freezing and thawing. The salt will crystallize within the pores of the unit and the repeated wetting and temperature cycling may produce an expansive force that will disintegrate the unit.

Chemical cleaning or sandblasting has the potential for causing serious damage to the masonry. Chemical cleaners produce soluble salts which may penetrate the masonry and cause development of new discolouration or contribute to new deterioration.

Performance of a masonry wall depends on the properties of both the brick and the mortar, and the compatability of the two constituents. The composition of mortar varies from the once very predominant limes and mortar to Portland cement with lime mortar. Today, masonry mortars predominate. Deterioration of cement was described in the previous section. The salts released by acidic attack on the mortar diffuse into the brick causing stress and subsequent spalling. Cement constituents of mortars may be relatively high in SO_4^{2-} and alkalis, and solutions of these constituents may accelerate attack on the brick.

3.6.4 Other Stones

Granites, gneisses, sandstones and slates, materials which do not contain large quantities of calcerous cements, are considerably less susceptible to damage by acidic deposition than those stones described in previous sections. Exposure of sandstone to the natural atmosphere can result in some discolouration as a result of oxidation of the pyrites in these rocks (Nriagu, 1978).

3.7 Paints

Painted surfaces are the most widely employed organic surfaces exposed to the atmosphere. Prolonged exposure of the surface to a number of environmental factors, eg, moisture, temperature, sunlight, air pollutants and atmospheric oxygen, can cause damage. Damage can include cracking, peeling, erosion and discolouration. Gradual erosion is most common because the commercially most important coatings have been tested and reformulated sufficiently to avoid the relatively undesirable types of damage such as cracking, delamination, etc.

There are four basic types of paint: (i) alkyd; (ii) acrylic latex house paint; (iii) coil coating finishes and (iv) nitrocellulose/acrylic coating (automotive finish). Paint damage is very dependent upon paint formulation. Paints typically consist of:

- pigments, eg, titanium dioxide, which provide colour, hiding power and durability;

- binder or vehicle, which consists of resin binders, solvents and additives, and provides the film forming properties;

- extender, eg, $CaCO_3$, inorganic silicates, mica and talc, which affects the gloss. Extenders may or may not be present, the higher the extender content, the lower the gloss. The ratio of pigments and extenders to the film forming ingredients determines the hardness, flexibility and permeability of the surface (Yocom and Baer, 1983).

Alkyd paints consist of an oil-modified alkyd resin and pigment (rutile TiO_2). Extenders such as calcium carbonate, barium sulfates, inorganic silicates are added to reduce the gloss. The paint dries by oxidation of the oil modified alkyd resin. Latex house paints consist of an acrylic emulsion, pigment (rutile TiO_2) and extenders (inorganic silicates and mica). The paint dries by evaporation of water from the film. Coil coating finishes can be made up of a vinyl, ureaalkyd, acrylic/polyester or fluorocarbon binder with pigment (75% rutile and 25% anatase TiO_2) and extender (inorganic silicates and $CaCO_3$). Automotive finishes contain nitrocellulose/acrylic and no extender.

Paints which contain a $CaCO_3$ extender are generally most susceptible to damage as a result of acidic deposition and have the largest erosion rates (Campbell, et al, 1974). Atmospheric SO_2, at concentrations greater than 1.0 ppm, most often causes erosion or wearing away of the paint surface (Stankunas et al, 1983). O_3 at the 1.0 ppm level, in the presence of UV light (sunlight) affects all coatings, except nitrocellulose/acrylic paint. Campbell et al concluded that SO_2 attack appears to be mainly on the extender component, whereas O_3 almost exclusively attacks the binder through a chain scissioning process. In the presence of ultraviolet light oil-based

coatings show severe breakdown of binder, followed by alkyd, urea-alkyd, acrylic latex and nitrocellulose/acrylic coatings. Paints which contain a moderate amount of $CaCO_3$ extender, when exposed to SO_2 at moderately high concentrations, exhibit a considerable decrease in carbonate content accompanied by the formation of sulfite and/or sulfate compounds. The increased water solubility of the sulfates leads to higher erosion levels.

3.8 Electrical Components

Electrical components susceptible to air pollutant damage include switches, relays, connectors, potentiometers, transmission wires and commutators. Air pollutants can cause an insulating film to form on metal components resulting in failure of the electrical connection (Yocom and Grappone, 1976). Particulate matter is considered to be the most important factor causing interference, more important than SO_2. Accumulation of particulates can lead to defects in manufacturing, or in extreme cases, short circuits in components in use. The major category of costs is avoidance costs. This includes protection of sensitive materials by building enclosures, or by using controlled environments and substitution of noncorroding materials, generally precious metals, for simple conductors. Some of these measures are, however, required even in the absence of air pollutants.

Steel core aluminum transmission wire has a built-in galvanic cell. This provides a good site for air pollution induced corrosion. Transmission lines, however, operate at above ambient temperatures, therefore the moisture required for corrosion is unlikely to form at the aluminum steel contact. A warm wire also tends to repel corrosive particles and the alternating electric field around the wire precludes electrostatic attraction of ionized particles. In the case of high DC power voltage, particles collecting on the surface could cause corrosion problems.

3.9 Textiles/Synthetics

The principal factors affecting the deterioration of textiles are light, humidity, acidity and particulates (Yocom and Baer, 1983). Humidity and sunlight often have a greater effect on fabric deterioration than measurable changes in pollution levels. Particulates cause the most significant and costly observed pollutant damage to textiles. The resultant frequent laundering and cleaning weakens fibres, especially cellulosics. Particulates also provide sites for gaseous adsorption of other pollutants. Polyesters and other synthetics attract "oily soil," nonsaponifiable soil, which forms a coating on the fibres in which particles become embedded. The oils may not be removed in a typical alkali wash and can scavenge dirt removed from other articles in the same wash load (Williams et al, 1980).

Nitrogen oxides (NO_x) cause loss of fibre strength and fading of textile dyes (Yocom and Baer, 1983). At NO_2 concentrations of 0.1-1.0 ppm, appreciable dye fading is observed. Dye fading increases with higher temperatures and relative humidities, however, the rate of fading as a function of exposure time appears to be nonlinear (Yocom and Baer, 1983). The substrate is generally a more important factor affecting fading than the dyestuff, eg, acetate fibre absorbs NO_x which later degrades the dyestuff; however, the same dyes when applied to wool show little fading upon exposure to NO_x. NO_x is believed to be responsible for the yellowing of white fabrics, the mechanism is, however, unknown (Williams et al, 1980).

SO_2/H_2SO_4 may cause hydrolytic damage to polypeptide links in nylon. The long molecular chains may be degraded or the crosslinks broken causing a loss in the strength of the material. SO_2/H_2SO_4 has not, however, been found to affect polyesters. The contribution of O_3 to fabric deterioration is not particularly significant at fairly low pollution levels. Generally, the economic lifetime of fabrics and textiles is so low that economically significant pollution damage is rare (Stankunas et al, 1983).

3.10 Glass

Some evidence suggests that stained glass treasures exposed to the atmosphere have deteriorated more rapidly in the past 30-40 years than in previous centuries. Weathering or deterioration of glass involves removing alkali cations such as potassium and sodium via reaction with SO_2 and water (Yocom and Baer, 1983). The glass becomes more and more opaque as only silica is left behind. A layer of "weatherstone," dust baked together with sulfates, or syngenite ($CaSO_4.K_2SO_4.H_2O$) crusts have also been observed to form on glass surfaces. Syngenite has been observed in locations with low concentrations of SO_2, suggesting that background levels of SO_2 are sufficient to produce the observed products (Yocom and Baer, 1983). The sulfates found in the weathering crusts could also be the by-products of the deterioration process (Yocom and Baer, 1983). Below the superficial skin, little corrosion nests appear in the glass and impurities. From these nests networks of cracks spread all over the glass until it is completely shattered (Nriagu, 1978). A contributing mechanism of decay stems from the storage of stained glass windows under damp conditions during the war. This permitted formation of a fissured hydrated layer that led to enhanced corrosion after reinstallation of the windows.

3.11 Cultural Property

Damage to cultural property from acidic deposition is a complex problem because of the high value placed upon such objects, their often irreplaceable nature and the wide range of material types represented (Yocom and Baer, 1983). The type and extent of damage is dependent upon the structural material. For discussion of the effects of air pollution on historic buildings and monuments, refer to the sections covering the specific building material.

4.0 SOCIAL COSTS

4.1 Methods of Calculation of Social Costs

Social costs, for the purpose of this report, are defined as an estimate of the value of damage to structural materials caused by emissions from Ontario Hydro's coal-fired generating stations during production of electricity for export. Calculation of social costs requires an estimate of the value of material susceptible to damage by the emissions, ie, acid rain.

The total economic value of a given material in use is a function of the amount of material in service, the labour content and the economic life of that material. Multiplication of this value by the percentage of that material actually exposed to air pollution gives a relative measure of the total value of material susceptible to air pollutant damage. Calculation of the extent and costs of damage due to acid rain or air pollution requires identification of:

i) the amount and distribution of susceptible materials in the environment;

ii) pollutant concentrations and sources;

iii) human response to the effects of air pollution; and

iv) the monetary values to be applied to the various effects and human responses to air pollution.

The validity of cost estimation is dependent upon the precision of the estimates of the amount and value of materials exposed to air pollution (Stankunas et al, 1983). The amount of material in place is generally estimated by determining the amount of a given material produced during a period equal to the standard use life of that material (Stankunas et al, 1983). An exposure factor is included to account for where or how a material is used and its resultant exposure to air pollutants (Stankunas et al, 1983). A flaw with this approach is the assumption that once a material is in place it remains unchanged except for deterioration, the impact of avoidance costs and practices is thereby ignored.

Quantification of the amount of material in place and its lifetime is difficult because information about use life is often based more on tax considerations than actual practice (Stankunas et al, 1983). Annual production figures, although commonly used, are of limited value in calculating the amount of material exposed. They do not include the costs associated with the use of the material and the possibility of double counting is high. If only materials with a high production rate are considered, then those with a somewhat lower total production, but perhaps a higher loss rate due to pollution damage may be missed.

Estimates of the distribution and surface area of exposed materials are generally based on population distribution patterns. This method can be inaccurate because areas with a low population density often have a high proportion of exposed materials, eg, industrial areas have a low population but a high proportion of galvanized steel structures.

Estimation of the economic impact of air pollution also requires information about the history of the air pollutants, pollutant loading coincident with the material distribution, the synergistic effects of multiple pollutants and associated environmental factors. It is very important to show that pollutant damage has a real influence on the use life of the material. The deterioration rate in the absence of pollutants must be established in order that dose-response relationships and the incremental costs of air pollution may be determined. Lifetime and maintenance costs for a given material in use in different environments are, however, very sensitive to nonpollutant variables at each location, ie, the environmental and usage factors can be very different.

Human response to the biophysical effects associated with air pollution can result in changes in behaviour, initiation of defensive actions, changes in perception and satisfaction or enjoyment. The amount of pollutant damage which is incurred before remedial actions are taken is influenced by physical, socioeconomic and aesthetic factors.

The theory of determination of the monetary values of damage resulting from air pollution, or the benefits of its reduction, is described in detail in a number of recent reports (OME, 1984; Kim, 1981, Jaksch, 1983). Calculation of the monetary value of air pollution damage to structural materials and the associated human response requires two component values, financial values and amenity values. Financial values are the monetary values of effects, goods or resources which are associated with markets and market prices. Amenity values are valuations that people have for resources and attributes, eg, cultural or historic properties, art objects, which for various reasons are not reflected in market prices. Amenity values are often estimated or people are asked directly what they are willing to pay (or require in compensation) for the relevant environmental effect. The sum of the financial and amenity values is the appropriate value of a good, an effect or a resource, to society.

Simple dose-response price multiplication procedures are often efficient means of estimating the economic value of air pollution materials damage. A number of such procedures have been developed. These include methods by Salmon (1970), Acres (1980), Haynie and Spence (1972), and Fink, Buttner and Boyd (1971). These procedures were reviewed in a paper by the Economic Division of Ontario Hydro (Kim, 1981). Each method is described briefly in the following sections.

4.1.1 Salmon's Method (1970)

Salmon (1970) estimated the total monetary damage to structural materials caused by air pollution using the formula:

$$L = P \times F \times N \times R \times V \qquad (27)$$

where L = the value of materials damage per year;
P = the annual production volume of a material;
F = a weighted average factor accounting for the proportion of material that is exposed to air pollution;
N = the weighted average economic life of the material based on usage;
R = a "labour factor" reflecting the in-place or as-used value of the material;
V = the "value of interaction" which is a measure of the portion of material lost each year to pollution, obtained by estimating the difference between the rate of material deterioration in polluted and nonpolluted environments expressed as dollars per year.

Salmon considered two types of materials damage: soiling and physical deterioration. Therefore, depending upon the nature of the damage, the term V is either the increased cost of cleaning or maintenance per year as a proportion of the unit price of the material concerned, or the proportion of a differential in annualized replacement costs in the unit price.

A major difficulty with Salmon's approach is that in calculation of the value of materials exposed to air pollution, economic production data reflect only final product values and do not include the value of service provided by a material. In the case of calculation of soiling costs, an economic value was not assigned to the loss in aesthetic beauty of a material.

4.1.2 Acres' Adaptation (1980) of Salmon's Method

Acres (1980) adapted Salmon's approach to facilitate calculation of the social costs incurred in selected regions in Ontario. Material specific damage for a region in Ontario (k) was calculated using equation 28:

$$L = C \times G_k \times N \times F \times R \times V \times I_k \qquad (28)$$

where L = annual rate of economic loss of material;
C = Ontario annual dollar consumption volume of material;
G_k = factor reducing C to zone scale based on the ratio of zone k population to Ontario population;
N = weighted average economic life of the material;
F = weighted average factor accounting for the percentage of material that is exposed to air pollution;
R = a labour factor to reflect the in-place or as-used value of the material;

V = value of interaction, a measure of the proportion of material lost each year to pollution, calculated by estimating the difference in rates of deterioration of a material in polluted and nonpolluted atmospheres;

I_k = a factor relating Ontario Hydro contributions of SO_2 in zone k to increases in background levels observed in going from rural to urban areas.

Equation 28 differs from Salmon's formula, Section 4.2.2, in that Salmon's factor for production, P, has been replaced by a consumption factor, C. This change was made to reflect the amount of structural materials actually in use in Ontario and avoids inclusion of materials produced for export. In addition, a population factor, G_k, and a SO_2 concentration factor, I_k, have been added. The consumption volume, C, on a national or provincial scale, is reduced to the regional scale on the basis of population by factor G_k. The interaction value, V, is multiplied by the factor I_k which relates the increase in air pollution in the regions under consideration to the difference in pollution levels assumed when deriving V. A linear relation between pollution level and materials' damage is assumed. I_k is calculated using equation 29.

$$I_k = \frac{SO_2 \text{ contribution by generating station to zone k}}{\left([SO_2]_{urban,measured} - [SO_2]_{rural,Salmon}\right)} \qquad (29)$$

Acres adapted Salmon's interaction values, V, to the situation in Ontario via equation 30.

$$V = \frac{V_{Salmon}}{[SO_2]_{urban,Salmon} - [SO_2]_{rural,Salmon}} \times \left([SO_2]_{\substack{urban \\ measured}} - [SO_2]_{\substack{rural \\ Salmon}}\right) \qquad (30)$$

Values of the "economic lifetime" of a material, N, and the labour factor, R, were taken directly from Salmon's report. Adaptation of Salmon's exposure factor, E, for use in Acres' formula, equation 28, is described in Acres' 1980 report.

Acres also considered materials' damage due to soiling. Potential costs for the cleaning of exterior walls and windows of houses were estimated using a modified version of Salmon's method for calculation of soiling costs, equation 31.

$$S = H \times B_k \times (A \times C_c \times F_c \times W \times C_w \times F_w) \qquad (31)$$

where H = the total number of houses in a zone;

B_k = a factor relating Ontario Hydro contributions of particulates to increases in particulate values in the regions under consideration;

A = total exterior wall area per house;

C_c = general cost of cleaning per square metre;

F_c = the increase in frequency of cleaning exterior walls in urban areas as a result of the increased particulate levels relative to rural areas;

W = total number of windows per house;

C_w = cleaning cost per window;

F_w = frequency of cleaning windows per year.

Ontario Hydro's contribution to particulate levels in zone k relative to background levels, B_k, was calculated using equation 32.

$$B_k = \frac{\text{particulate contribution by generating station to zone k}}{([\text{particulate}]_{\text{urban}} - [\text{particulate}]_{\text{rural}})} \quad (32)$$

The exterior wall area, A, for an average size house, ie, somewhere between a 3-bedroom bungalow and a 3-bedroom, 2-storey home, was estimated to be 181.5 m^2. The increased frequency of cleaning exterior walls (F_c) as a result of increased particulate levels in urban areas relative to rural areas was set at 0.75. The frequency of cleaning windows per year, F_w, was assumed to be 2. Acres assumed that many house owners would not wash all their exterior walls between repaints, and many would clean exterior walls and windows themselves. To account for this, 10% of the calculated estimates was assumed to represent the soiling costs which could be incurred in practise.

4.1.3 Haynie and Spence (1972)

The method developed by Haynie and Spence (1972) yields an estimate of the cost of exterior repainting as a result of excessive concentrations of suspended particulates. The method is based on the formula

$$C = y \times \left[\frac{F_u \times D_u}{(F_r \times D_r) + (F_u \times D_u)}\right] \times \left[\frac{L_r - L_u}{L_r}\right] \times R \quad (33)$$

where C = cost of repainting;

y = annual dollar value of paint produced;

F_r, F_u = frequencies of repainting in rural (r) and urban (u) areas;

D_r, D_u = the consumption distribution, in rural (r) and urban (u) areas, of paint produced such that $D_r+D_u = 1$;

L_r, L_u = service lives of exterior paint in rural and urban areas;

R = labour factor to convert manufacture value to consumer value.

Loss estimates were developed for four paint classes: oil coating, automotive refinishing, maintenance and household. The expected service lives, L_r and L_u, were generally best guess estimates. In the case of household paints, expected service lives for rural and urban areas were estimated from the Michelson and Tourin (1967), and Booz, Allen studies (1970).

4.1.4 Fink, Buttner and Boyd (1971)

Fink, Buttner and Boyd (1971) estimated the monetary loss of materials corrosion caused by air pollution using an approach based on component systems rather than specific materials. To illustrate, steel storage tanks, chainlink fencing, etc were considered instead of galvanized steel. This approach was selected because they believed that the value, lifetime and exposure of a given material to air pollution are very dependent upon where and how the material is used. Individual corrosion rates were estimated for nine categories of susceptible materials and structures. The method for establishing economic damage involved:

i) estimation of the total number of each component system or structure in use;

ii) conversion of this number to the exposed surface area in square feet;

iii) calculation of the annual extra cost/unit area of either protection or maintenance, ie, by paint, or early replacement, for each system. Costs were based on national shipment value data for selected materials and articles with the assumption that 80% of these materials are located in "polluted" areas.

The total of the combined area (ii) and the annual cost figures (iii) yielded the national (US) loss for each item.

4.2 Estimation of Social Costs

The estimate of the social costs (mills/kWh) that may be incurred in Ontario due to the environmental impact of fossil-fuel fired production of electricity for export is the sum of the total value of damage to structural materials (ΣD_r), soiling costs and the value of damage to cultural property divided by the amount of electricity exported (kWh), equation 34,

$$E = \frac{(\Sigma D_r + S + H)}{P} \qquad (34)$$

where E = estimate of social costs per kWh due to export of electricity;

ΣD_r = total value of materials damage in region r (eg, sum of value of damage to zinc, concrete, etc. due to corrosion, erosion, etc);

S = soiling costs;

H = value of damage to cultural properties;

P = number of kWh of electricity produced by fossil-fuel fired generating stations for export.

The value of materials damage is estimated using equation 35.

$$D_r = C \times L \times V \times E \times I_r \times P_r \qquad (35)$$

where D_r = annual economic value of damage to a specific material in region r;

C = annual consumption volume of material in Ontario;

L = average economic life of the material;

V = value added or labour factor;

E = exposure factor;

I_r = interaction value in region r;

P_r = population factor for region r.

This method of calculation of the value of damage to a specific material is based on the Acres (1980) and Salmon (1970) methods, with some modifications derived from the OME model for estimation of social costs (OME,1984). The derivation of values for each factor is described in the following sections.

The cost of air pollution damage is estimated for only the following economically significant materials:

- concrete
- zinc (galvanized steel)
- aluminum
- copper
- nickel
- brick
- stone
- glass
- paint.

To simplify calculations, Ontario is divided into five regions: Northern Ontario, Southern Ontario and three 50-km zones surrounding each of the three fossil-fuel fired generating stations which provide

power for export, Lakeview TGS, Nanticoke TGS and Lambton TGS, see Figure 2. The cost estimates are based on materials damage due to dry deposition of SO_2 (all regions) and wet deposition of SO_2 + SO_4^{2-} (Northern and Southern Ontario regions only). Pollutant ambient concentration and deposition data were provided by CTS, see Section 4.2.5. Damage due to wet deposition of SO_4^{2-} was considered only in the far field due to the very small amount deposited in the near field (<50 km from the source) and the lack of reliable data for describing the near field situation.

The total value of materials damage in Ontario is, therefore, the sum of the annual economic value of damage to each of the materials listed above from SO_2 (dry deposition) and SO_2 + SO_4^{2-} (wet deposition) in each of the five regions of Ontario.

Social costs are calculated for the base year 1982 and projections are made for 1986 and 1989.

4.2.1 Consumption Volume of Material - Ontario (C)

The annual dollar consumption volumes of materials in Ontario used to calculate D_r are based on the 1979 consumption volumes derived by Acres (1980). The 1979 estimates were converted to 1982 values using the construction price index for nonresidential building materials. In 1979 the construction price index was 208.7 (Canadian Statistical Review, December 1981) and in 1982 it was 275.3 (Canadian Statistical Review, January 1984). Therefore, to obtain 1982 consumption volumes, Acres' 1979 values were multiplied by (275.3/208.7).

The construction price index for nonresidential construction materials is forecast to be 370.0 in 1986 and 472.6 in 1989 (using 1982 as the base year). 1986 consumption volumes are therefore obtained by multiplying the 1982 values by (370.0/275.3) and 1989 consumption volumes are estimated by multiplying 1982 volumes by (472.6/275.3). It is assumed that during the period 1979 to 1989 the overall rate of consumption or use of the material will remain constant. Table 2 lists the consumption volumes (C) calculated for the years 1982, 1986 and 1989.

4.2.2 Economic Life of Material (L)

The weighted average economic lifetimes of materials were taken from Salmon's (1970) report. The values are based on the guidelines and rules of the US Treasury Department. The lifetimes of selected materials are given in Table 3.

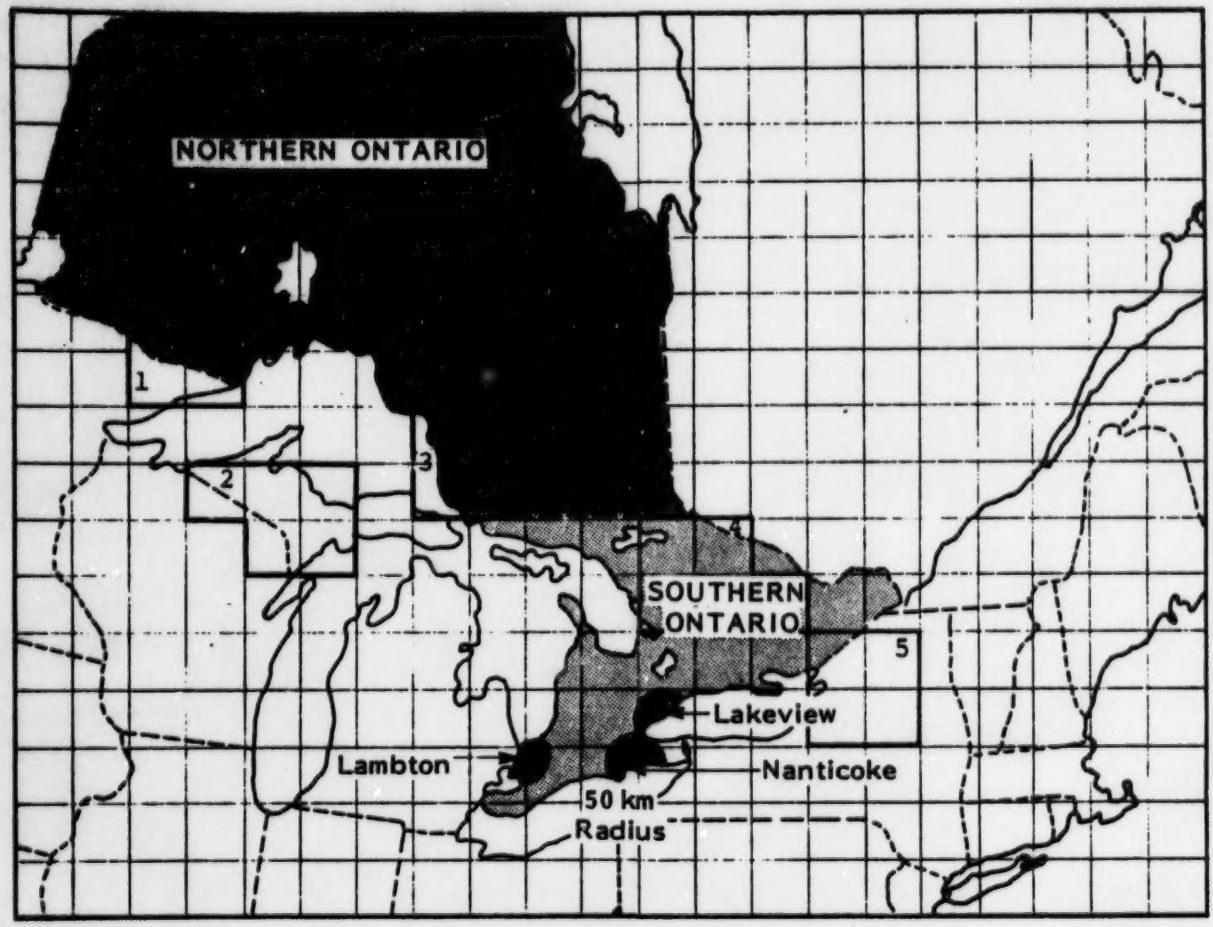


FIGURE 2

Division of Ontario into 5 study regions: Northern Ontario, Southern Ontario, Lakeview, Nanticoke and Lambton. Numbered boxes designate Fisher's LRT model sensitive areas:

1. Lakehead, 2. Upper Michigan, 3. Algoma, 4. Muskoka-Haliburton, 5. Adirondacks.

TABLE 2

CONSUMPTION VOLUME OF MATERIAL
- ONTARIO (C)
($)

Material	1979 ($x10^6$)	1982 ($x10^6$)	1986 ($x10^6$)	1989 ($x10^6$)
Concrete	310.7	409.9	550.9	703.7
Zinc	33.1	43.7	58.7	75.0
Copper	142.2	187.6	252.1	322.1
Aluminum	174.2	229.8	308.9	394.5
Nickel	27.7	36.5	49.1	62.7
Tin	3.3	4.4	5.9	7.6
Paint	84.9	112.0	150.5	192.3
Brick	44.8	59.1	79.4	101.5
Stone	8.6	11.3	15.2	19.4
Glass	127.2	167.8	225.5	288.1

TABLE 3

ECONOMIC LIFE OF SELECTED
MATERIALS (L)

Material	Life (y)
Concrete	40
Zinc	36
Copper	22
Aluminum	16
Nickel	14
Tin	13
Paint	4
Brick	40
Stone	50
Glass	30

4.2.3 Value Added Factor (V)

The value added factor is a labour factor which is included in the calculation of materials damage to reflect the in-place or as-used value of the material. The original values were taken from Salmon's (1970) report; however, Salmon's values were based on 1968 US economic conditions. Salmon's labour factors were therefore adjusted to reflect 1982 economic conditions in Ontario. In 1968 the ratio of total construction costs to material costs was 2.19 and in 1982 the ratio was 2.66 (Statistics Canada, 64-201). Each of Salmon's material specific labour factors were multiplied by (2.66/2.19) to give 1982 values, see Table 4.

TABLE 4

VALUE ADDED FACTORS FOR SPECIFIC MATERIALS

Material	Salmon (1970) (1968)	1982	1986	1989
Concrete	2.6	3.2	3.2	3.3
Zinc	2.3	2.8	2.8	2.9
Copper	2.4	2.9	3.0	3.0
Aluminum	2.0	2.4	2.5	2.5
Nickel	2.3	2.8	2.8	2.9
Tin	2.1	2.6	2.6	2.6
Paint	3.3	4.0	4.1	4.1
Brick	2.3	2.8	2.8	2.9
Stone	2.3	2.8	2.8	2.9
Glass	2.3	2.8	2.8	2.9

Estimates of the value added factors for the years 1986 and 1989 are also based on Salmon's 1968 labour factor. The ratio of total construction costs to material costs for the years 1986 and 1989 are forecast to be 2.71 and 2.75, respectively. These values are based on the trend observed in the ratios during the period 1980-1983. Salmon's 1968 values were therefore multiplied by (2.71/2.19) and (2.75/2.19) to yield value added factors for the years 1986 and 1989, respectively, see Table 4.

4.2.4 Exposure Factor (E)

The exposure factor, a weighted average factor, is included in the calculation of D_r to account for the percentage of consumed material that is actually exposed to air pollution. Acres' (1980) exposure factors were used for calculation of damage due to dry deposition of SO_2. In the case of damage due to wet deposition of SO_4^{2-}, Acres' (1980) exposure factors were reduced by 50% (E^1) to reflect the fact that not all surfaces subject to atmospheric corrosion will be exposed to deposition by rain (OME, 1984). The exposure factors for the two cases (E, E^1) are listed in Table 5.

TABLE 5

EXPOSURE FACTORS FOR SELECTED MATERIALS

Material	$\bar{E}$ (SO_2 dry)	$\bar{E}'$ ($SO_2+SO_4^{2-}$ wet)
Concrete	0.67	0.34
Zinc	0.93	0.47
Copper	0.67	0.34
Aluminum	0.67	0.34
Nickel	0.67	0.34
Tin	0.53	0.27
Paint	0.93	0.47
Brick	0.93	0.47
Stone	0.93	0.47
Glass	0.93	0.47

4.2.5 Interaction Factor (I_r)

The interaction factor is a measure of the proportion of material lost each year to air pollution. It is calculated by estimating the difference in rates of deterioration of a material in polluted and nonpolluted atmospheres. Interaction factors are material, pollutant and region specific. Thus, the interaction factor (y^{-1}) is given by

$$I_r = \frac{R \times F_{ir}}{Q_{ave}} \qquad (36)$$

where R = interaction rate (physical unit/y/pollutant concentration) ($\mu g\ m^{-3}$);

F_{ir} = concentration of pollutant i in region r ($\mu g\ m^{-3}$);

Q_{ave} = appropriate physical unit in which material loss is estimated, eg, weight, thickness, per cent tensile strength.

For this study, interaction values are specified for dry SO_2 deposition (I_r) and for wet $SO_2+SO_4^{2-}$ deposition (I_r'). I_r' is 40% of I_r to reflect the fact that $SO_2+SO_4^{2-}$ in precipitation is likely to be in contact with materials a shorter time than dry deposited SO_2, (OME, 1984) equation 37.

$$I_r' = I_r \times \frac{40}{100} \qquad (37)$$

To facilitate calculations, region estimates of wet deposition of $SO_2+SO_4^{2-}$ from anthropogenic sources were converted to an equivalent concentration of SO_2, equation 38 (OME, 1984).

$$y = \frac{x}{0.14} \quad (38)$$

where x = S deposition in $g/m^2/yr$ and y = SO_2 concentration in $\mu g\ m^{-3}$.

The interaction factors for all materials except zinc and copper were derived from those reported by Salmon (1970). Salmon's interaction values were based on a difference of 0.045 ppm SO_2 (117.8 $\mu g\ m^{-3}$) between urban and rural atmospheres. Salmon's values were therefore divided by 117.8 $\mu g\ m^{-3}$ SO_2 and multiplied by the equivalent SO_2 concentration in the region under consideration to give the region specific factor. Therefore,

$$I_r = \frac{I_{r(Salmon)}}{117.8\ \mu g\ m^{-3}} \times [SO_2]_r \quad (39)$$

where $[SO_2]$ = equivalent concentration of SO_2 in region r ($\mu g\ m^{-3}$).

In the case of zinc and copper, corrosion data more recent than Salmon's work is available. In 1970 Haynie and Upham reported that the corrosion of zinc varies linearly with SO_2 concentration and relative humidity according to equation 40.

$$Y = 0.001028\ (H - 48.8)\ S \quad (40)$$

where Y = zinc corrosion rate ($\mu m/y$)
S = ave. SO_2 concentration ($\mu g\ m^{-3}$)
H = ave. relative humidity (%).

The interaction value can be calculated using

$$I_r = \frac{Y}{Q_{ave.}} \quad (41)$$

where Y = zinc corrosion rate ($\mu m/y$)
$Q_{ave.}$ = thickness of zinc plate = 75 μm.

If H = 80% then the interaction factor, I_r, for zinc is 4.28×10^{-4} $[SO_2]_r\ y^{-1}$. The interaction factor adjusted for wet sulfate deposition, I_r', is 1.71×10^{-4} $[SO_2]_r\ y^{-1}$.

In 1976 Kucera reported the following corrosion rates for copper:

urban atm.: 35 $\mu g\ S/m^3$ (70 $\mu g\ SO_2/m^3$) = 1.0 $\mu m/y$
rural atm.: 5 $\mu g\ S/m^3$ (10 $\mu g\ SO_2/m^3$) = 0.6 $\mu m/y$

Linear extrapolation indicates that in the absence of pollution copper corrodes at a rate of approximately 0.53 $\mu m/y$. Therefore, the corrosion rate of copper is 6.85×10^{-3} $[SO_2]_r$ $\mu m\ y^{-1}$.

The interaction value is given by

$$I_r = \frac{6.85 \times 10^{-3}\ [SO_2]_r}{Q_{ave.}} \quad (42)$$

where $Q_{ave.}$ = thickness of Cu = 320 μm.

Therefore $I_r = 2.14 \times 10^{-5} [SO_2]_r \ y^{-1}$ and $I_r' = 8.56 \times 10^{-6} [SO_2]_r \ y^{-1}$.

The material and pollutant specific interaction values are given in Table 6. The probable range for each interaction factor is set at a factor of 2 in either direction. One-half the estimated value of interaction is set as the lower limit and twice the value as the upper limit.

TABLE 6

INTERACTION FACTORS - REGION SPECIFIC (y^{-1})

Material	$I_{r(Salmon)}$	I_r	I_r'
Concrete	1×10^{-3}	$8.49 \times 10^{-6} [SO_2]_r$	$3.40 \times 10^{-6} [SO_2]_r$
Zinc	2.9×10^{-2}	$4.28 \times 10^{-4} [SO_2]_r$	$1.71 \times 10^{-4} [SO_2]_r$
Copper	2.0×10^{-3}	$2.14 \times 10^{-5} [SO_2]_r$	$8.56 \times 10^{-6} [SO_2]_r$
Aluminum	2.1×10^{-3}	$1.78 \times 10^{-5} [SO_2]_r$	$7.13 \times 10^{-6} [SO_2]_r$
Nickel	2.5×10^{-2}	$2.12 \times 10^{-4} [SO_2]_r$	$8.49 \times 10^{-5} [SO_2]_r$
Tin	2.6×10^{-2}	$2.21 \times 10^{-4} [SO_2]_r$	$8.83 \times 10^{-5} [SO_2]_r$
Paint	5.0×10^{-2}	$4.20 \times 10^{-4} [SO_2]_r$	$1.70 \times 10^{-4} [SO_2]_r$
Brick	1.0×10^{-3}	$8.49 \times 10^{-6} [SO_2]_r$	$3.40 \times 10^{-6} [SO_2]_r$
Stone	2.3×10^{-3}	$1.95 \times 10^{-5} [SO_2]_r$	$7.81 \times 10^{-6} [SO_2]_r$
Glass	1.0×10^{-5}	$8.49 \times 10^{-8} [SO_2]_r$	$3.40 \times 10^{-8} [SO_2]_r$

The SO_2 and $SO_2+SO_4^{2-}$ deposition data required to calculate I_r and I_r' are listed in Table 7. The table presents only those $SO_2+SO_4^{2-}$ levels due to Ontario Hydro's fossil-fuel fired production of electricity for export. $SO_2+SO_4^{2-}$ wet deposition data for the regions of Northern and Southern Ontario were estimated by the Atmospheric Research Section (ARS) using their version of Fisher's Statistical Long-Range Transport model (LRT). This model generates estimates of SO_2 and SO_4^{2-} deposition in five sensitive areas in and around Ontario, see Figure 2. SO_2 and SO_4^{2-} deposition data modelled for the Algoma region were assumed to be representative of air pollutant concentrations in Northern Ontario. Estimates for Southern Ontario were based on the Muskoka-Haliburton region's deposition data. Deposition data for Lakehead, one of the five receptor areas in the ARS model and located in Northern Ontario, were not chosen to represent pollutant concentrations and deposition in Northern Ontario. This was because the LRT model does not include the point sources of pollution located in Manitoba which affect air quality in Northern Ontario.

Table 7

1982, 1986 and 1989 Dry SO_2 and Wet $SO_2 + SO_4^{2-}$ C
Deposition Data for Five Regions in Ontario ($\mu g\ SO_2\ m^{-3}$)

Region	1982 $(SO_2)_{dry}$	1982 $(SO_2+ SO_4^{2-})_{wet}$	1986 $(SO_2)_{dry}$	1986 $(SO_2+ SO_4^{2-})_{wet}$	1989 $(SO_2)_{dry}$	1989 $(SO_2+ SO_4^{2-})_{wet}$
Northern Ontario (Algoma)	$3.47x10^{-2}$	$3.36x10^{-2}$	$3.89x10^{-2}$[a]	$3.79x10^{-2}$	$3.89x10^{-2}$	$3.76x10^{-2}$
Southern Ontario (Muskoka-Haliburton)	$1.09x10^{-1}$	$1.03x10^{-1}$	$6.27x10^{-2}$[a]	$5.86x10^{-2}$	$6.20x10^{-2}$[a]	$5.82x10^{-2}$
Lakeview TGS	0.45	N/A	$6.42x10^{-2}$[b]	N/A	$3.80x10^{-2}$[b]	N/A
Nanticoke TGS	0.59	N/A	0.36[b]	N/A	0.21[b]	N/A
Lambton TGS	2.13	N/A	0.84[b]	N/A	0.45[b]	N/A

[a] 1981 data used as base year for projections.

[b] Background pollutant concentrations are assumed to remain constant. Only Ontario Hydro's contribution to pollutant levels in 1986 and 1989 adjusted.

[c] Data originally reported in units of $g\ SO_4^{2-}\ m^{-2}$.

The use of the relatively low pollutant levels modelled for the Lakehead region to describe Northern Ontario may therefore lead to artificially low results. Estimates of SO_2 and $SO_2+SO_4^{2-}$ deposition for Algoma are believed to provide a conservative estimate of the situation in Northern Ontario.

Estimates of SO_2 and $SO_2+SO_4^{2-}$ pollutant levels in 1986 and 1989 were based on 1981 emissions and deposition data. 1982 deposition data were not used because INCO, a major sulfate emitter affecting all of Ontario, was not in operation for much of 1982. 1982 SO_2 and $SO_2+SO_4^{2-}$ deposition levels are therefore atypical.

The material, pollutant, region and year specific interaction factors used to calculate D_r are listed in Tables 8-10.

4.2.6 Population Factor (P_r)

The distribution of materials within Ontario is assumed to be directly related to population density. The population factor, P_r, was calculated by dividing the population of region r by the total population of Ontario. Population factors were calculated for the five regions considered in the study; Northern Ontario, Southern Ontario and the three 50-km zones around Lakeview TGS, Nanticoke TGS and Lambton TGS, see Figure 2. 1981 Ontario population census data were used to calculate $P_r(1982)$. Population factors for 1986 and 1989 were estimated using Ontario population forecasts for the years 1986 and 1991, respectively. The division of Ontario's counties into the five study regions, for the purpose of counting, is given in Appendix A. The population factors, P_r, calculated are listed in Table 11.

4.2.7 Calculation of D_r

The economic value of materials damage (D_r) due to dry deposition of SO_2 and wet deposition of $SO_2+SO_4^{2-}$ was calculated using equation 35

$$D_r = C \times L \times V \times E \times I_r \times P_r \qquad (35)$$

D_r was estimated for the materials: concrete, zinc, copper, aluminum, nickel, tin, paint, brick, stone and glass, in the regions of Northern Ontario, Southern Ontario, Lakeview TGS, Nanticoke TGS and Lambton TGS, for the years 1982, 1986 and 1989. The material, region and year specific values for C, L, V, E, I_r and P_r used to calculate D_r are listed in Tables 2-11.

In 1982 a total of 10 577 GWh of fossil-fuel generated power was exported. The total value of materials damage due to dry and wet deposition of SO_2/SO_4^{2-} resulting from production of this electricity was $964,000. Forecasts for 1986 suggest that 7 713 GWh of fossil-fuel generated electricity will be exported. This will result in approximately $388,000 worth of materials damage.

Table 8

Pollutant and Region Specific Interaction Factors - 1982 (y^{-1})

Material	$I_{N\ Ont}$	$I'_{N\ Ont}$	$I_{S\ Ont}$	$I'_{S\ Ont}$	$I_{Lakeview}$	$I'_{Lakeview}$	$I_{Nanticoke}$	$I'_{Nanticoke}$	$I_{Lambton}$	$I'_{Lambton}$
Concrete	2.95×10^{-7}	1.14×10^{-7}	9.25×10^{-7}	3.50×10^{-7}	3.82×10^{-6}	N/A	5.01×10^{-6}	N/A	1.81×10^{-5}	N/A
Zinc	1.49×10^{-5}	5.75×10^{-6}	4.67×10^{-5}	1.76×10^{-5}	1.93×10^{-4}	N/A	2.53×10^{-4}	N/A	9.12×10^{-4}	N/A
Copper	7.43×10^{-7}	2.88×10^{-7}	2.33×10^{-6}	8.82×10^{-7}	9.63×10^{-6}	N/A	1.27×10^{-5}	N/A	4.56×10^{-5}	N/A
Aluminum	6.18×10^{-7}	2.40×10^{-7}	1.94×10^{-6}	7.34×10^{-7}	8.01×10^{-6}	N/A	1.05×10^{-5}	N/A	3.79×10^{-5}	N/A
Nickel	7.36×10^{-6}	2.85×10^{-6}	2.31×10^{-5}	8.74×10^{-6}	9.54×10^{-5}	N/A	1.25×10^{-4}	N/A	4.52×10^{-4}	N/A
Tin	7.67×10^{-6}	2.97×10^{-6}	2.41×10^{-5}	9.09×10^{-6}	9.95×10^{-5}	N/A	1.30×10^{-4}	N/A	4.71×10^{-4}	N/A
Paint	1.46×10^{-5}	5.71×10^{-6}	4.58×10^{-5}	1.75×10^{-5}	1.89×10^{-4}	N/A	2.48×10^{-4}	N/A	8.95×10^{-4}	N/A
Brick	2.95×10^{-7}	1.14×10^{-7}	9.25×10^{-7}	3.50×10^{-7}	3.82×10^{-6}	N/A	5.01×10^{-6}	N/A	1.81×10^{-5}	N/A
Stone	6.77×10^{-7}	2.62×10^{-7}	2.13×10^{-6}	8.04×10^{-7}	8.76×10^{-6}	N/A	1.15×10^{-5}	N/A	4.15×10^{-5}	N/A
Glass	2.95×10^{-9}	1.14×10^{-9}	9.25×10^{-9}	3.50×10^{-9}	3.82×10^{-8}	N/A	5.01×10^{-8}	N/A	1.81×10^{-7}	N/A

Table 9

Pollutant and Region Specific Interaction Factors - 1986 (y^{-1})

Material	$I_{N\ Ont}$	$I'_{N\ Ont}$	$I_{S\ Ont}$	$I'_{S\ Ont}$	$I^*_{Lakeview}$	$I^*_{Nanticoke}$	$I^*_{Lambton}$
Concrete	3.30×10^{-7}	1.29×10^{-7}	5.32×10^{-7}	1.99×10^{-7}	5.45×10^{-7}	3.05×10^{-6}	7.13×10^{-6}
Zinc	1.66×10^{-5}	6.48×10^{-6}	2.68×10^{-5}	1.00×10^{-5}	2.75×10^{-5}	1.54×10^{-4}	3.60×10^{-4}
Copper	8.32×10^{-7}	3.24×10^{-7}	1.34×10^{-6}	5.02×10^{-7}	1.37×10^{-6}	7.70×10^{-6}	1.80×10^{-5}
Aluminum	6.92×10^{-7}	2.70×10^{-7}	1.12×10^{-6}	4.18×10^{-7}	1.14×10^{-6}	6.41×10^{-6}	1.50×10^{-5}
Nickel	8.25×10^{-6}	3.22×10^{-6}	1.33×10^{-5}	4.98×10^{-6}	1.36×10^{-5}	7.63×10^{-5}	1.78×10^{-4}
Tin	8.60×10^{-6}	3.35×10^{-6}	1.39×10^{-5}	5.17×10^{-6}	1.42×10^{-5}	7.96×10^{-5}	1.86×10^{-4}
Paint	1.63×10^{-5}	6.44×10^{-6}	2.63×10^{-5}	9.96×10^{-6}	2.70×10^{-5}	1.51×10^{-4}	3.53×10^{-4}
Brick	3.30×10^{-7}	1.29×10^{-7}	5.32×10^{-7}	1.99×10^{-7}	5.45×10^{-7}	3.06×10^{-6}	7.13×10^{-6}
Stone	7.59×10^{-7}	2.96×10^{-7}	1.22×10^{-6}	4.58×10^{-7}	1.25×10^{-6}	7.02×10^{-6}	1.64×10^{-5}
Glass	3.30×10^{-9}	1.29×10^{-9}	5.32×10^{-9}	1.99×10^{-9}	5.45×10^{-9}	3.06×10^{-8}	7.13×10^{-8}

* $I'_{Lakeview}$, $I'_{Nanticoke}$, $I'_{Lambton}$ not available.

Table 10

Pollutant and Region Specific Interaction Factors - 1989 (y^{-1})

Material	$I_{N\ Ont}$	$I'_{N\ Ont}$	$I_{S\ Ont}$	$I'_{S\ Ont}$	$I^*_{Lakeview}$	$I^*_{Nanticoke}$	$I^*_{Lambton}$
Concrete	3.30×10^{-7}	1.28×10^{-7}	5.26×10^{-7}	1.98×10^{-7}	3.23×10^{-7}	1.78×10^{-6}	3.82×10^{-6}
Zinc	1.66×10^{-5}	6.43×10^{-6}	2.65×10^{-5}	9.95×10^{-6}	1.63×10^{-5}	8.99×10^{-5}	1.93×10^{-4}
Copper	8.32×10^{-7}	3.22×10^{-7}	1.33×10^{-6}	4.98×10^{-7}	8.13×10^{-7}	4.49×10^{-6}	9.63×10^{-6}
Aluminum	6.92×10^{-7}	2.68×10^{-7}	1.10×10^{-6}	4.15×10^{-7}	6.76×10^{-7}	3.74×10^{-6}	8.01×10^{-6}
Nickel	8.25×10^{-6}	3.19×10^{-6}	1.31×10^{-5}	4.94×10^{-6}	8.06×10^{-6}	4.45×10^{-5}	9.54×10^{-5}
Tin	8.60×10^{-6}	3.32×10^{-6}	1.37×10^{-5}	5.14×10^{-6}	8.40×10^{-6}	4.64×10^{-5}	9.95×10^{-5}
Paint	1.63×10^{-5}	6.39×10^{-6}	2.60×10^{-5}	9.89×10^{-6}	1.60×10^{-5}	8.82×10^{-5}	1.89×10^{-4}
Brick	3.30×10^{-7}	1.28×10^{-7}	5.26×10^{-7}	1.98×10^{-7}	3.23×10^{-7}	1.78×10^{-6}	3.82×10^{-6}
Stone	7.59×10^{-7}	2.94×10^{-7}	1.21×10^{-6}	4.55×10^{-7}	7.41×10^{-7}	4.10×10^{-6}	8.78×10^{-6}
Glass	3.30×10^{-9}	1.28×10^{-9}	5.26×10^{-9}	1.98×10^{-9}	3.23×10^{-9}	1.78×10^{-8}	3.82×10^{-8}

* $I'_{Lakeview}$, $I'_{Nanticoke}$, $I'_{Lambton}$ not available.

Table 11

Population Factors (P_r)

Region	1982 Population (Total)	P_r	1986 Population (Total)	P_r	1989 Population[a] (Total)	P_r
Northern Ontario	453 142	0.053	487 604	0.054	503 802	0.055
Southern Ontario	4 427 228	0.513	4 681 179	0.523	4 874 827	0.528
Lakeview	3 431 370	0.398	3 454 232	0.386	3 508 261	0.380
Nanticoke	204 747	0.024	214 116	0.024	220 552	0.024
Lambton	108 620	0.013	117 884	0.013	123 183	0.013
Ontario (Total)	8 625 107		8 955 015		9 230 625	

[a] Actually 1991 Ontario population forecast.

In 1989, 5 585 GWh of fossil-fuel produced electricity are expected to be exported causing approximately $395,000 worth of materials damage.

A detailed breakdown of these values by material, year, region and pollutant is given in Appendix B in Tables B-1 to B-24. The results summarized by pollutant, region, material and year are given in Tables 12-14.

4.3 Calculation of Social Costs

An estimate of the social costs that may be incurred in Ontario due to the environmental impact of fossil-fuel fired production of electricity for export is obtained by summing the total cost of damage to structural materials (ΣD_r), soiling costs (S) and the value of damage to cultural property (H). Dividing this value by the amount of electricity exported (P) yields the cost per kWh.

$$SC = \frac{\Sigma D_r + S + H}{P} \qquad (34)$$

Estimation of the economic value of materials' damage, D_r, for the years 1982, 1986 and 1989 was described in Section 4.2.7. Soiling costs and a value for damage to cultural property have not been estimated. Although Salmon and Acres have reported procedures for the calculation of soiling costs, Sections 4.1.1 and 4.1.2, these methods were not implemented in this study due to the arbitrary manner in which the required data are selected. For the purpose of this work, any fraction of ΣD_r may be chosen to represent S. The values of air pollution damage to cultural property often quoted in the popular literature are not well founded or referenced and have therefore not been used. As a result, equation 34 for estimation of social costs simplifies to the sum of the values of damage to the previously selected structural materials, equation 41.

$$SC = \frac{\Sigma D_r}{P} \qquad (41)$$

Estimation of ΣD_r was described in Section 4.2.7. In 1982, 10 577 GWh of fossil-fuel generated power were exported resulting in approximately $964,000 worth of materials damage. Therefore, in 1982 the social costs to structural materials were approximately 0.1 mills/kWh. In 1986, 7 713 GWh of fossil fuel power are expected to be exported and the value of materials damage is estimated to be $388,000. The social costs would therefore be 0.05 mills/kWh. In 1989, 5 585 GWh of exported fossil fuel power would cause $395,000 worth of damage. Therefore the social costs are estimated to be 0.07 mills/kWh.

5.0 CONCLUSIONS

The effects of air pollution, specifically fossil-fuel fired generating station emissions, and natural environmental factors on the deterioration of exposed structural materials have been reviewed. Differentiation of pollutant-induced damage and deterioration due to natural weathering processes is difficult. A major environmental

Table 12

Summary $D_{Ontario}$ (1982) ($)

Material	$D_{Northern\ Ontario}$ $[SO_2]_{dry}$	$[SO_2+SO_4^{2-}]_{wet}$	$D_{Southern\ Ontario}$ $[SO_2]_{dry}$	$(SO_2+SO_4^{2-}]_{wet}$	$D_{Lakeview}$ $[SO_2]_{dry}$	$D_{Nanticoke}$ $[SO_2]_{dry}$	$D_{Lambton}$ $[SO_2]_{dry}$	$D_{Ontario}$
Concrete	$5.50x10^2$	$1.08x10^2$	$1.67x10^4$	$3.20x10^3$	$5.34x10^4$	$4.22x10^3$	$8.27x10^3$	$8.64x10^4$
Zinc	$3.24x10^3$	$6.31x10^2$	$9.81x10^4$	$1.87x10^4$	$3.15x10^5$	$2.49x10^4$	$4.86x10^4$	$5.09x10^5$
Copper	$3.16x10^2$	$6.21x10^1$	$9.59x10^3$	$1.84x10^3$	$3.07x10^4$	$2.44x10^3$	$4.75x10^3$	$4.97x10^4$
Aluminum	$1.93x10^2$	$3.81x10^1$	$5.88x10^3$	$1.13x10^3$	$1.88x10^4$	$1.49x10^3$	$2.91x10^3$	$3.04x10^4$
Nickel	$3.74x10^2$	$7.35x10^1$	$1.14x10^4$	$2.18x10^3$	$3.64x10^4$	$2.89x10^3$	$5.63x10^3$	$5.89x10^4$
Tin	$3.20x10^1$	6.32	$9.75x10^2$	$1.87x10^2$	$3.12x10^3$	$2.46x10^2$	$4.83x10^2$	$5.05x10^3$
Paint	$1.29x10^3$	$2.55x10^2$	$3.92x10^4$	$7.56x10^3$	$1.23x10^5$	$9.92x10^3$	$1.94x10^4$	$2.01x10^5$
Brick	$9.62x10^1$	$1.88x10^1$	$2.92x10^3$	$5.59x10^2$	$9.36x10^3$	$7.40x10^2$	$1.45x10^3$	$1.51x10^4$
Stone	$5.28x10^1$	$1.03x10^1$	$1.61x10^3$	$3.07x10^2$	$5.13x10^3$	$4.06x10^2$	$7.94x10^2$	$8.31x10^3$
Glass	2.05	$4.00x10^{-1}$	$6.22x10^1$	$1.19x10^1$	$1.99x10^2$	$1.58x10^1$	$3.08x10^1$	$3.22x10^2$
								$9.64x10^5$

Table 13

$D_{Ontario}$ - Summary - 1986 ($)

Material	$D_{Northern\ Ontario}$ $[SO_2]_{dry}$	$[SO_2+SO_4^{2-}]_{wet}$	$D_{Southern\ Ontario}$ $[SO_2]_{dry}$	$[SO_2+SO_4^{2-}]_{wet}$	$D_{Lakeview}$ $[SO_2]_{dry}$	$D_{Nanticoke}$ $[SO_2]_{dry}$	$D_{Lambton}$ $[SO_2]_{dry}$	$D_{Ontario}$
Concrete	$8.42x10^2$	$1.67x10^2$	$1.31x10^4$	$2.50x10^3$	$9.94x10^3$	$3.46x10^3$	$4.38x10^3$	$3.44x10^4$
Zinc	$4.93x10^3$	$9.73x10^2$	$7.71x10^4$	$1.45x10^4$	$5.84x10^4$	$2.03x10^4$	$2.58x10^4$	$2.02x10^5$
Copper	$5.01x10^2$	$9.90x10^1$	$7.81x10^3$	$1.49x10^3$	$5.90x10^3$	$2.06x10^3$	$2.61x10^3$	$2.05x10^4$
Aluminum	$3.09x10^2$	$6.13x10^1$	$4.85x10^3$	$9.18x10^2$	$3.64x10^3$	$1.27x10^3$	$1.61x10^3$	$1.27x10^4$
Nickel	$5.75x10^2$	$1.14x10^2$	$8.97x10^3$	$1.70x10^3$	$6.77x10^3$	$2.36x10^3$	$2.98x10^3$	$2.35x10^4$
Tin	$4.91x10^1$	9.74	$7.68x10^2$	$1.46x10^2$	$5.79x10^2$	$2.02x10^2$	$2.56x10^2$	$1.96x10^3$
Paint	$2.02x10^3$	$4.03x10^2$	$3.16x10^4$	$6.04x10^3$	$2.39x10^4$	$8.32x10^3$	$1.05x10^4$	$8.28x10^4$
Brick	$1.47x10^2$	$2.91x10^1$	$2.30x10^3$	$4.35x10^2$	$1.74x10^3$	$6.07x10^2$	$7.67x10^2$	$6.29x10^3$
Stone	$8.11x10^1$	$1.60x10^1$	$1.26x10^3$	$2.40x10^2$	$9.55x10^2$	$3.33x10^2$	$4.22x10^2$	$3.31x10^3$
Glass	3.14	$6.20x10^{-1}$	$4.90x10^1$	9.27	$3.71x10^1$	$1.29x10^1$	$1.63x10^1$	$1.28x10^2$
								$3.88x10^5$

Table 14

$D_{Ontario}$ Summary - 1989 ($)

Material	$D_{Northern\ Ontario}$ $[SO_2]_{dry}$	$D_{Northern\ Ontario}$ $[SO_2+SO_4^{2-}]_{wet}$	$D_{Southern\ Ontario}$ $[SO_2]_{dry}$	$D_{Southern\ Ontario}$ $[SO_2+SO_4^{2-}]_{wet}$	$D_{Lakeview}$ $[SO_2]_{dry}$	$D_{Nanticoke}$ $[SO_2]_{dry}$	$D_{Lambton}$ $[SO_2]_{dry}$	$D_{Ontario}$
Concrete	$1.13x10^3$	$2.22x10^2$	$1.73x10^4$	$3.30x10^3$	$7.64x10^3$	$2.66x10^3$	$3.09x10^3$	$3.53x10^4$
Zinc	$6.65x10^3$	$1.30x10^3$	$1.02x10^5$	$1.93x10^4$	$4.51x10^4$	$1.57x10^4$	$1.82x10^4$	$2.08x10^5$
Copper	$6.52x10^2$	$1.28x10^2$	$1.00x10^4$	$1.90x10^3$	$4.40x10^3$	$1.53x10^3$	$1.78x10^3$	$2.04x10^4$
Aluminum	$4.02x10^2$	$7.91x10^1$	$6.14x10^3$	$1.18x10^3$	$2.72x10^3$	$9.49x10^2$	$1.10x10^3$	$1.26x10^4$
Nickel	$7.74x10^2$	$1.52x10^2$	$1.18x10^4$	$2.26x10^3$	$5.22x10^3$	$1.82x10^3$	$2.12x10^3$	$2.41x10^4$
Tin	$6.44x10^1$	$1.27x10^1$	$9.85x10^2$	$1.88x10^2$	$4.35x10^2$	$1.52x10^2$	$1.76x10^2$	$2.01x10^3$
Paint	$2.63x10^3$	$5.21x10^2$	$4.03x10^4$	$7.74x10^3$	$1.78x10^4$	$6.21x10^3$	$7.21x10^3$	$8.24x10^4$
Brick	$1.99x10^2$	$3.90x10^1$	$3.04x10^3$	$5.79x10^2$	$1.34x10^3$	$4.68x10^2$	$5.44x10^2$	$6.21x10^3$
Stone	$1.09x10^2$	$2.14x10^1$	$1.67x10^3$	$3.18x10^2$	$7.37x10^2$	$2.57x10^2$	$2.99x10^2$	$3.41x10^3$
Glass	4.23	$8.29x10^{-1}$	$6.47x10^1$	$1.23x10^1$	$2.86x10^1$	9.96	$1.16x10^1$	$1.32x10^2$
								$3.95x10^5$

factor resulting in deterioration of materials in water. In the absence of moisture very little atmospheric corrosion or decay would be observed. Sulfate (SO_2^{4-}) and the chloride ion (Cl^-) have a wide distribution in the environment and their economic impact in terms of corrosion is high. SO_2/SO_4^{2-} is a major emission from fossil-fuel fired power plants.

Air pollution damage to the following structural materials was examined: metals, building stone, paints, textiles and glass. Structural materials most susceptible to damage have been reformulated and/or coated to increase resistance to damage. To illustrate, the amount of bare galvanized steel exposed directly to the environment has decreased sharply in recent years due primarily to the development of coatings which adhere to the metal.

Social costs, for the purpose of this report, are defined as an estimate of the value of damage to structural materials caused by emissions from Ontario Hydro's coal-fired generating stations during production of electricity for export. Calculation of social costs requires an estimate of the value of materials damage, an estimate of soiling costs and an estimate of the value of damage to cultural/historic property. An estimate of materials damage was obtained using an adaptation of Salmon's (1970) and Acres' (1980) procedures. Damage to the following structural materials was estimated: concrete, zinc, copper, aluminum, nickel, tin, paint, brick, stone and glass. Only damage due to dry deposition of SO_2 and wet deposition of $SO_2+SO_4^{2-}$ within Ontario was considered. Soiling costs and a value of damage to cultural/historic property were not estimated because of a lack of reliable information. The social costs are therefore simply an estimate of the cost of SO_2/SO_4^{2-} damage to structural materials. In 1982 the costs were estimated to be 0.1 mills/kWh in 1986, 0.05 mills/kWh and in 1989, they are predicted to be 0.07 mills/kWh. The range of these values is set at a factor of 2 in either direction, one-half the estimated value as the lower limit and twice the value as the upper limit.

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APPENDIX A

DIVISION OF ONTARIO COUNTIES INTO 8 REGIONS

All counties in Ontario were separated into 8 regions (Northern Ontario, Southern Ontario, Lakeview TGS, Nanticoke TGS, and Lambton TGS) to facilitate estimation of the populations of these regions relative to the population of Ontario as a whole, P_r. Population data are given for the years 1981, 1986 and 1991.

Region/ County	% County Population Within This Region	1981 Population	1986 Population	1991 Population
Northern Ontario:				
Algoma	25	34 025	34 354	36 050
Cochrane	100	96 875	104 262	107 667
Kenora	100	59 421	60 164	61 159
Rainey River	100	22 798	25 001	25 122
Sudbury TD	28	44 738	52 966	55 659
		453 142	487 604	503 802
Southern Ontario:				
Algoma	75	99 528	103 061	108 149
Brant	13.9	14 489	14 934	15 461
Bruce	100	60 020	63 033	66 206
Dufferin	100	31 145	36 757	41 162
Dundas	100	18 946	17 444	16 913
Durham	100	283 639	291 653	313 413
Elgin	100	69 707	72 503	74 256
Essex	100	312 476	333 868	344 136
Frontenac	100	108 133	116 548	119 251
Glengarry	100	20 254	19 696	20 042
Grenville	100	27 176	28 056	29 220
Grey	100	73 824	77 711	80 888
Haldimand-Norfolk	7.1	6 387	6 737	6 931
Haliburton	100	11 361	11 733	12 248
Hamilton-Wentworth	3	12 343	12 929	13 116
Hastings	100	106 883	114 219	118 037
Huron	100	56 127	57 891	59 179
Kent	91.6	98 032	104 404	107 594
Lambton	19.3	23 815	25 903	27 100
Lanark	100	45 676	43 639	43 316
Leeds	100	53 765	54 767	55 767
Lennox-Addington	100	33 040	33 713	34 104
Manitoulin	100	11 001	11 404	11 864
Middlesex	100	318 184	322 686	328 236
Muskoka D.M.	100	38 370	39 672	41 237
Niagara	84.3	310 467	326 176	333 594
Nipissing	100	80 268	91 891	97 010
Northumberland	100	64 966	68 437	70 623
Ottawa-Carleton	100	546 849	510 319	586 951
Oxford	94.3	81 033	87 953	91 518

Region/ County	% County Population Within This Region	1981 Population	1986 Population	1991 Population
Parry Sound	100	33 528	33 214	33 650
Peel	1.4	6 870	6 689	7 399
Perth	100	66 096	67 300	67 856
Peterborough	100	102 452	106 050	108 655
Prescott	100	30 365	32 203	33 786
Prince Edward	100	22 336	22 847	22 946
Renfrew	100	87 484	92 916	94 730
Russell	100	22 412	23 936	26 146
Simcoe	100	225 071	241 007	255 661
Stormont	100	61 927	64 241	65 506
Sudbury R.M.	100	27 068	29 245	30 285
Sudbury T.D.	72	115 041	136 197	143 122
Victoria	100	47 854	45 629	46 854
Waterloo	100	305 496	337 137	358 443
Wellington	96	124 255	140 969	151 668
York	52	131 068	141 872	160 598
		4 427 228	4 681 179	4 874 827
Lakeview				
Halton	100	253 883	270 222	291 152
Hamilton-Wentworth	91.1	374 826	392 616	398 289
Niagara	15	55 243	58 038	59 358
Peel	98.6	483 861	471 127	521 084
Toronto	100	2 137 395	2 125 396	2 083 813
Wellington	4	5 177	5 874	6 320
York	48	120 985	130 959	148 245
		3 431 370	3 454 232	3 508 261
Nanticoke				
Brant	86.1	89 938	92 508	95 772
Haldimand-Norfolk	92.9	83 069	88 157	90 683
Hamilton-Wentworth	5.9	24 275	25 427	25 795
Niagara	0.7	2 578	2 708	2 771
Oxford	5.7	4 877	5 316	5 532
		204 747	214 116	220 552
Lambton				
Kent	8.4	8 990	9 574	9 867
Lambton	80.7	99 630	108 310	113 316
		108 620	117 884	123 183
Ontario Total		8 625 107	8 955 015	9 230 625

APPENDIX B

DETAILED CALCULATIONS OF D_r AND ASSUMPTIONS

Tables B-1 to B-24 present the detailed calculations of the value of materials damage (D_r). D_r, due to dry deposition of SO_2 and wet deposition of $SO_2 + SO_4^{2-}$, was calculated for concrete, zinc, copper, aluminum, nickel, tin, paint, brick, stone and glass, in the regions of Northern Ontario, Southern Ontario, Lakeview, Nanticoke and Lambton, for the years 1982, 1986 and 1989. Damage due to wet deposition of sulfate was considered only in the far field (>50 km from the source) due to the very small amount deposited in the near field and the lack of reliable data for describing the near field situation.

To facilitate calculations, the following assumptions were made:

(1) during the period 1979-1989 the overall rate of consumption or use of structural materials will remain constant;

(2) the trend in the ratio of total construction costs to material costs observed for the period 1980-1983 will continue until 1989;

(3) only 50% of all materials exposed to air pollution are exposed to wet pollutant deposition;

(4) interaction factors for wet $SO_2 + SO_4^{2-}$ deposition are 40% of those values specified for dry SO_2 deposition (Section 4.2.5);

(5) SO_2 and SO_4^{2-} deposition data modelled for the Algoma region are representative of SO_2/SO_4^{2-} deposition patterns in Northern Ontario;

(6) SO_2 and SO_4^{2-} deposition data modelled for the Muskoka-Haliburton region are representative of SO_2/SO_4^{2-} deposition patterns in Southern Ontario;

(7) 1991 Ontario population forecasts represent 1989 population patterns;

(8) Ontario Hydro's contribution, due to exports, to total dry SO_2 deposition in the Algoma (ie, Northern Ontario) region during the years 1982, 1986 and 1989 is set at 1%;

(9) Ontario Hydro's contribution, due to export, to total dry SO_2 deposition in the Muskoka-Haliburton (ie, Southern Ontario) region during 1982 is set at 2% and for the years 1986 and 1989 at 1%.

Table B-1

Calculation of D_r for r = N Ont, $[SO_2]_{dry}$, 1982

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	I N Ont	P N Ont	D N Ont
Concrete	409.9	40	3.2	0.67	$2.95x10^{-7}$	0.053	$5.50x10^{2}$
Zinc	43.7	36	2.8	0.93	$1.49x10^{-5}$	0.053	$3.24x10^{3}$
Copper	187.6	22	2.9	0.67	$7.43x10^{-7}$	0.053	$3.16x10^{2}$
Aluminum	229.6	16	2.4	0.67	$6.18x10^{-7}$	0.053	$1.93x10^{2}$
Nickel	36.5	14	2.8	0.67	$7.36x10^{-6}$	0.053	$3.74x10^{2}$
Tin	4.4	13	2.6	0.53	$7.67x10^{-6}$	0.053	$3.20x10^{1}$
Paint	112.0	4	4.0	0.93	$1.46x10^{-5}$	0.053	$1.29x10^{3}$
Brick	59.1	40	2.8	0.93	$2.95x10^{-7}$	0.053	$9.62x10^{1}$
Stone	11.3	50	2.8	0.93	$6.77x10^{-7}$	0.053	$5.28x10^{1}$
Glass	167.8	30	2.8	0.93	$2.95x10^{-9}$	0.053	2.05
							$6.15x10^{3}$

Table B-2

Calculation of D_r for r = N Ont, $[SO_2+SO_4^{2-}]_{wet}$, 1982

$D_r = CxLxVxEx I_r x P_r$

Material	C ($x10^6$)	L	V	E'	I' N Ont	P N Ont	$D_{N\ Ont}$
Concrete	409.9	40	3.2	0.34	$1.14x10^{-7}$	0.053	$1.08x10^{2}$
Zinc	43.7	36	2.8	0.47	$5.75x10^{-6}$	0.053	$6.31x10^{2}$
Copper	187.6	22	2.9	0.34	$2.88x10^{-7}$	0.053	$6.21x10^{1}$
Aluminum	229.6	16	2.4	0.34	$2.40x10^{-7}$	0.053	$3.81x10^{1}$
Nickel	36.5	14	2.8	0.34	$2.85x10^{-6}$	0.053	$7.35x10^{1}$
Tin	4.4	13	2.6	0.27	$2.97x10^{-6}$	0.053	6.32
Paint	112.0	4	4.0	0.47	$5.71x10^{-6}$	0.053	$2.55x10^{2}$
Brick	59.1	40	2.8	0.47	$1.14x10^{-7}$	0.053	$1.88x10^{1}$
Stone	11.3	50	2.8	0.47	$2.62x10^{-7}$	0.053	$1.03x10^{1}$
Glass	167.8	30	2.8	0.47	$1.14x10^{-9}$	0.053	$4.00x10^{-1}$
							$1.20x10^{3}$

Table B-3

Calculation of D_r for r = S Ont, $[SO_2]_{dry}$, 1982

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{S\ Ont}$	$P_{S\ Ont}$	$D_{S\ Ont}$
Concrete	409.9	40	3.2	0.67	$9.25x10^{-7}$	0.513	$1.67x10^{4}$
Zinc	43.7	36	2.8	0.93	$4.67x10^{-5}$	0.513	$9.81x10^{4}$
Copper	187.6	22	2.9	0.67	$2.33x10^{-6}$	0.513	$9.59x10^{3}$
Aluminum	229.6	16	2.4	0.67	$1.94x10^{-6}$	0.513	$5.88x10^{3}$
Nickel	36.5	14	2.8	0.67	$2.31x10^{-5}$	0.513	$1.14x10^{4}$
Tin	4.4	13	2.6	0.53	$2.41x10^{-5}$	0.513	$9.75x10^{2}$
Paint	112.0	4	4.0	0.93	$4.58x10^{-5}$	0.513	$3.92x10^{4}$
Brick	59.1	40	2.8	0.93	$9.25x10^{-7}$	0.513	$2.92x10^{3}$
Stone	11.3	50	2.8	0.93	$2.13x10^{-6}$	0.513	$1.61x10^{3}$
Glass	167.8	30	2.8	0.93	$9.25x10^{-9}$	0.513	$6.22x10^{1}$
							$1.86x10^{5}$

Table B-4

Calculation of D_r for r = S Ont, $[SO_2+SO_4^{2-}]_{wet}$, 1982

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E'	$I'_{S\ Ont}$	$P_{S\ Ont}$	$D_{S\ Ont}$
Concrete	409.9	40	3.2	0.34	$3.50x10^{-7}$	0.513	$3.20x10^{3}$
Zinc	43.7	36	2.8	0.47	$1.76x10^{-5}$	0.513	$1.87x10^{4}$
Copper	187.6	22	2.9	0.34	$8.82x10^{-7}$	0.513	$1.84x10^{3}$
Aluminum	229.6	16	2.4	0.34	$7.34x10^{-7}$	0.513	$1.13x10^{3}$
Nickel	36.5	14	2.8	0.34	$8.74x10^{-6}$	0.513	$2.18x10^{3}$
Tin	4.4	13	2.6	0.27	$9.09x10^{-6}$	0.513	$1.87x10^{2}$
Paint	112.0	4	4.0	0.47	$1.75x10^{-5}$	0.513	$7.56x10^{3}$
Brick	59.1	40	2.8	0.47	$3.50x10^{-7}$	0.513	$5.59x10^{2}$
Stone	11.3	50	2.8	0.47	$8.04x10^{-7}$	0.513	$3.07x10^{2}$
Glass	167.8	30	2.8	0.47	$3.50x10^{-9}$	0.513	$1.19x10^{1}$
							$3.57x10^{4}$

Table B-5

Calculation of D_r for r = Lakeview, $[SO_2]_{dry}$, 1982

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{Lakeview}$	$P_{Lakeview}$	$D_{Lakeview}$
Concrete	409.9	40	3.2	0.67	$3.82x10^{-6}$	0.398	$5.34x10^{4}$
Zinc	43.7	36	2.8	0.93	$1.93x10^{-4}$	0.398	$3.15x10^{5}$
Copper	187.6	22	2.9	0.67	$9.63x10^{-6}$	0.398	$3.07x10^{4}$
Aluminum	229.6	16	2.4	0.67	$8.01x10^{-6}$	0.398	$1.88x10^{4}$
Nickel	36.5	14	2.8	0.67	$9.54x10^{-5}$	0.398	$3.64x10^{4}$
Tin	4.4	13	2.6	0.53	$9.95x10^{-5}$	0.398	$3.12x10^{3}$
Paint	112.0	4	4.0	0.93	$1.89x10^{-4}$	0.398	$1.23x10^{5}$
Brick	59.1	40	2.8	0.93	$3.82x10^{-6}$	0.398	$9.36x10^{3}$
Stone	11.3	50	2.8	0.93	$8.76x10^{-6}$	0.398	$5.13x10^{3}$
Glass	167.8	30	2.8	0.93	$3.82x10^{-8}$	0.398	$1.99x10^{2}$
							$5.95x10^{5}$

Table B-6

Calculation of D_r for r = Nanticoke, $[SO_2]_{dry}$, 1982

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{Nanticoke}$	$P_{Nanticoke}$	$D_{Nanticoke}$
Concrete	409.9	40	3.2	0.67	$5.01x10^{-6}$	0.024	$4.22x10^{3}$
Zinc	43.7	36	2.8	0.93	$2.53x10^{-4}$	0.024	$2.49x10^{4}$
Copper	187.6	22	2.9	0.67	$1.27x10^{-5}$	0.024	$2.44x10^{3}$
Aluminum	229.6	16	2.4	0.67	$1.05x10^{-5}$	0.024	$1.49x10^{3}$
Nickel	36.5	14	2.8	0.67	$1.25x10^{-4}$	0.024	$2.89x10^{3}$
Tin	4.4	13	2.6	0.53	$1.30x10^{-4}$	0.024	$2.46x10^{2}$
Paint	112.0	4	4.0	0.93	$2.48x10^{-4}$	0.024	$9.92x10^{3}$
Brick	59.1	40	2.8	0.93	$5.01x10^{-6}$	0.024	$7.40x10^{2}$
Stone	11.3	50	2.8	0.93	$1.15x10^{-5}$	0.024	$4.06x10^{2}$
Glass	167.8	30	2.8	0.93	$5.01x10^{-8}$	0.024	$1.58x10^{1}$
							$4.73x10^{4}$

Table B-7

Calculation of D_r for r = Lambton, $[SO_2]_{dry}$, 1982

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{Lambton}$	$P_{Lambton}$	$D_{Lambton}$
Concrete	409.9	40	3.2	0.67	$1.81x10^{-5}$	0.013	$8.27x10^{3}$
Zinc	43.7	36	2.8	0.93	$9.12x10^{-4}$	0.013	$4.86x10^{4}$
Copper	187.6	22	2.9	0.67	$4.56x10^{-5}$	0.013	$4.75x10^{3}$
Aluminum	229.6	16	2.4	0.67	$3.79x10^{-5}$	0.013	$2.91x10^{3}$
Nickel	36.5	14	2.8	0.67	$4.52x10^{-4}$	0.013	$5.63x10^{3}$
Tin	4.4	13	2.6	0.53	$4.71x10^{-4}$	0.013	$4.83x10^{2}$
Paint	112.0	4	4.0	0.93	$8.95x10^{-4}$	0.013	$1.94x10^{4}$
Brick	59.1	40	2.8	0.93	$1.81x10^{-5}$	0.013	$1.45x10^{3}$
Stone	11.3	50	2.8	0.93	$4.15x10^{-5}$	0.013	$7.94x10^{2}$
Glass	167.8	30	2.8	0.93	$1.81x10^{-7}$	0.013	$3.08x10^{1}$
							$9.23x10^{4}$

Table B-8

Social Costs (1982)

Region (r)	Pollutant	D_r ($)
Northern Ontario	SO_2 (dry)	6.15×10^3
	$SO_2 + SO_4^{2-}$ (wet)	1.20×10^3
Southern Ontario	SO_2 (dry)	1.86×10^5
	$SO_2 + SO_4^{2-}$ (wet)	3.57×10^4
Lakeview	SO_2 (dry)	5.95×10^5
Nanticoke	SO_2 (dry)	4.73×10^4
Lambton	SO_2 (dry)	9.23×10^4
		9.64×10^5

Fossil-fuel generated electricity exported = 10 577 GWh

$= 1.06 \times 10^{10}$ kWh

$$\therefore \text{Social costs} = \frac{\$9.64 \times 10^5}{1.06 \times 10^{10} \text{ kWh}}$$

$$= 0.1 \text{ mills/kWh}$$

Table B-9

Calculation of D_r for r = N Ontario, $[SO_2]_{dry}$, 1986

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{N\ Ont}$	$P_{N\ Ont}$	$D_{N\ Ont}$
Concrete	550.9	40	3.2	0.67	$3.30x10^{-7}$	0.054	$8.42x10^{2}$
Zinc	58.7	36	2.8	0.93	$1.66x10^{-5}$	0.054	$4.93x10^{3}$
Copper	252.1	22	3.0	0.67	$8.32x10^{-7}$	0.054	$5.01x10^{2}$
Aluminum	308.9	16	2.5	0.67	$6.92x10^{-7}$	0.054	$3.09x10^{2}$
Nickel	49.1	14	2.8	0.67	$8.25x10^{-6}$	0.054	$5.75x10^{2}$
Tin	5.9	13	2.6	0.53	$8.60x10^{-6}$	0.054	$4.91x10^{1}$
Paint	150.5	4	4.1	0.93	$1.63x10^{-5}$	0.054	$2.02x10^{3}$
Brick	79.4	40	2.8	0.93	$3.30x10^{-7}$	0.054	$1.47x10^{2}$
Stone	15.2	50	2.8	0.93	$7.59x10^{-7}$	0.054	$8.11x10^{1}$
Glass	225.5	30	2.8	0.93	$3.30x10^{-9}$	0.054	3.14
							$9.46x10^{3}$

Table B-10

Calculation of D_r for r = N Ontario, $[SO_2+SO_4^{2-}]_{wet}$, 1986

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E'	$I'_{N\ Ont}$	$P_{N\ Ont}$	$D_{N\ Ont}$
Concrete	550.9	40	3.2	0.34	$1.29x10^{-7}$	0.054	$1.67x10^{2}$
Zinc	58.7	36	2.8	0.47	$6.48x10^{-6}$	0.054	$9.73x10^{2}$
Copper	252.1	22	3.0	0.34	$3.24x10^{-7}$	0.054	$9.90x10^{1}$
Aluminum	308.9	16	2.5	0.34	$2.70x10^{-7}$	0.054	$6.13x10^{1}$
Nickel	49.1	14	2.8	0.34	$3.22x10^{-6}$	0.054	$1.14x10^{2}$
Tin	5.9	13	2.6	0.27	$3.35x10^{-6}$	0.054	9.74
Paint	150.5	4	4.1	0.47	$6.44x10^{-6}$	0.054	$4.03x10^{2}$
Brick	79.4	40	2.8	0.47	$1.29x10^{-7}$	0.054	$2.91x10^{1}$
Stone	15.2	50	2.8	0.47	$2.96x10^{-7}$	0.054	$1.60x10^{1}$
Glass	225.5	30	2.8	0.47	$1.29x10^{-9}$	0.054	$6.20x10^{-1}$
							$1.87x10^{3}$

Table B-11

Calculation of D_r for r = S Ontario, $[SO_2]_{dry}$, 1986

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{S\ Ont}$	$P_{S\ Ont}$	$D_{S\ Ont}$
Concrete	550.9	40	3.2	0.67	$5.32x10^{-7}$	0.523	$1.31x10^{4}$
Zinc	58.7	36	2.8	0.93	$2.68x10^{-5}$	0.523	$7.71x10^{4}$
Copper	252.1	22	3.0	0.67	$1.34x10^{-6}$	0.523	$7.81x10^{3}$
Aluminum	308.9	16	2.5	0.67	$1.12x10^{-6}$	0.523	$4.85x10^{3}$
Nickel	49.1	14	2.8	0.67	$1.33x10^{-5}$	0.523	$8.97x10^{3}$
Tin	5.9	13	2.6	0.53	$1.39x10^{-5}$	0.523	$7.68x10^{2}$
Paint	150.5	4	4.1	0.93	$2.63x10^{-5}$	0.523	$3.16x10^{4}$
Brick	79.4	40	2.8	0.93	$5.32x10^{-7}$	0.523	$2.30x10^{3}$
Stone	15.2	50	2.8	0.93	$1.22x10^{-6}$	0.523	$1.26x10^{3}$
Glass	225.5	30	2.8	0.93	$5.32x10^{-9}$	0.523	$4.90x10^{1}$
							$1.48x10^{5}$

Table B-12

Calculation of D_r for r = S Ontario, $[SO_2+SO_4^{2-}]_{wet}$, 1986

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E'	$I'_{S\ Ont}$	$P_{S\ Ont}$	$D_{S\ Ont}$
Concrete	550.9	40	3.2	0.34	$1.99x10^{-7}$	0.523	$2.50x10^{3}$
Zinc	58.7	36	2.8	0.47	$1.00x10^{-5}$	0.523	$1.45x10^{4}$
Copper	252.1	22	3.0	0.34	$5.02x10^{-7}$	0.523	$1.49x10^{3}$
Aluminum	308.9	16	2.5	0.34	$4.18x10^{-7}$	0.523	$9.18x10^{2}$
Nickel	49.1	14	2.8	0.34	$4.98x10^{-6}$	0.523	$1.70x10^{3}$
Tin	5.9	13	2.6	0.27	$5.17x10^{-6}$	0.523	$1.46x10^{2}$
Paint	150.5	4	4.1	0.47	$9.96x10^{-6}$	0.523	$6.04x10^{3}$
Brick	79.4	40	2.8	0.47	$1.99x10^{-7}$	0.523	$4.35x10^{2}$
Stone	15.2	50	2.8	0.47	$4.58x10^{-7}$	0.523	$2.40x10^{2}$
Glass	225.5	30	2.8	0.47	$1.99x10^{-9}$	0.523	9.27
							$2.80x10^{4}$

Table B-13

Calculation of D_r for r = Lakeview, $[SO_2]_{dry}$, 1986

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{Lakeview}$	$P_{Lakeview}$	$D_{Lakeview}$
Concrete	550.9	40	3.2	0.67	$5.45x10^{-7}$	0.386	$9.94x10^{3}$
Zinc	58.7	36	2.8	0.93	$2.75x10^{-5}$	0.386	$5.84x10^{4}$
Copper	252.1	22	3.0	0.67	$1.37x10^{-6}$	0.386	$5.90x10^{3}$
Aluminum	308.9	16	2.5	0.67	$1.14x10^{-6}$	0.386	$3.64x10^{3}$
Nickel	49.1	14	2.8	0.67	$1.36x10^{-5}$	0.386	$6.77x10^{3}$
Tin	5.9	13	2.6	0.53	$1.42x10^{-5}$	0.386	$5.79x10^{2}$
Paint	150.5	4	4.1	0.93	$2.70x10^{-5}$	0.386	$2.39x10^{4}$
Brick	79.4	40	2.8	0.93	$5.45x10^{-7}$	0.386	$1.74x10^{3}$
Stone	15.2	50	2.8	0.93	$1.25x10^{-6}$	0.386	$9.55x10^{2}$
Glass	225.5	30	2.8	0.93	$5.45x10^{-9}$	0.386	$3.71x10^{1}$
							$1.12x10^{5}$

Table B-14

Calculation of D_r for r = Nanticoke, $[SO_2]_{dry}$, 1986

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{Nanticoke}$	$P_{Nanticoke}$	$D_{Nanticoke}$
Concrete	550.9	40	3.2	0.67	$3.05x10^{-6}$	0.024	$3.46x10^{3}$
Zinc	58.7	36	2.8	0.93	$1.54x10^{-4}$	0.024	$2.03x10^{4}$
Copper	252.1	22	3.0	0.67	$7.70x10^{-6}$	0.024	$2.06x10^{3}$
Aluminum	308.9	16	2.5	0.67	$6.41x10^{-6}$	0.024	$1.27x10^{3}$
Nickel	49.1	14	2.8	0.67	$7.63x10^{-5}$	0.024	$2.36x10^{3}$
Tin	5.9	13	2.6	0.53	$7.96x10^{-5}$	0.024	$2.02x10^{2}$
Paint	150.5	4	4.1	0.93	$1.51x10^{-4}$	0.024	$8.32x10^{3}$
Brick	79.4	40	2.8	0.93	$3.06x10^{-6}$	0.024	$6.07x10^{2}$
Stone	15.2	50	2.8	0.93	$7.02x10^{-6}$	0.024	$3.33x10^{2}$
Glass	225.5	30	2.8	0.93	$3.06x10^{-8}$	0.024	$1.29x10^{1}$
							$3.89x10^{4}$

Table B-15

Calculation of D_r for r = Lambton, $[SO_2]_{dry}$, 1986

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{Lambton}$	$P_{Lambton}$	$D_{Lambton}$
Concrete	550.9	40	3.2	0.67	$7.13x10^{-6}$	0.013	$4.38x10^{3}$
Zinc	58.7	36	2.8	0.93	$3.60x10^{-4}$	0.013	$2.58x10^{4}$
Copper	252.1	22	3.0	0.67	$1.80x10^{-5}$	0.013	$2.61x10^{3}$
Aluminum	308.9	16	2.5	0.67	$1.50x10^{-5}$	0.013	$1.61x10^{3}$
Nickel	49.1	14	2.8	0.67	$1.78x10^{-4}$	0.013	$2.98x10^{3}$
Tin	5.9	13	2.6	0.53	$1.86x10^{-4}$	0.013	$2.56x10^{2}$
Paint	150.5	4	4.1	0.93	$3.53x10^{-4}$	0.013	$1.05x10^{4}$
Brick	79.4	40	2.8	0.93	$7.13x10^{-6}$	0.013	$7.67x10^{2}$
Stone	15.2	50	2.8	0.93	$1.64x10^{-5}$	0.013	$4.22x10^{2}$
Glass	225.5	30	2.8	0.93	$7.13x10^{-8}$	0.013	$1.63x10^{1}$
							$4.93x10^{4}$

Table B-16

Social Costs (1986)

Region (r)	Pollutant	D_r ($)
Northern Ontario	SO_2 (dry)	9.46×10^3
	$SO_2 + SO_4^{2-}$ (wet)	1.87×10^3
Southern Ontario	SO_2 (dry)	1.48×10^5
	$SO_2 + SO_4^{2-}$ (wet)	2.80×10^4
Lakeview	SO_2 (dry)	1.12×10^5
Nanticoke	SO_2 (dry)	3.89×10^4
Lambton	SO_2 (dry)	4.93×10^4
		3.88×10^5

Fossil-fuel generated electricity to be exported = 7713 GWh

$= 7.71 \times 10^9$ kWh

$$\therefore \text{Social Costs} = \frac{\$3.88 \times 10^5}{7.71 \times 10^9 \text{ kWh}}$$

$$= 0.05 \text{ mills/kWh}$$

Table B-17

Calculation of D_r for r = N Ontario, $[SO_2]_{dry}$, 1989

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{N\ Ontario}$	$P_{N\ Ontario}$	$D_{N\ Ontario}$
Concrete	703.7	40	3.3	0.67	$3.30x10^{-7}$	0.055	$1.13x10^{3}$
Zinc	75.0	36	2.9	0.93	$1.66x10^{-5}$	0.055	$6.65x10^{3}$
Copper	322.1	22	3.0	0.67	$8.32x10^{-7}$	0.055	$6.52x10^{2}$
Aluminum	394.5	16	2.5	0.67	$6.92x10^{-7}$	0.055	$4.02x10^{2}$
Nickel	62.7	14	2.9	0.67	$8.25x10^{-6}$	0.055	$7.74x10^{2}$
Tin	7.6	13	2.6	0.53	$8.60x10^{-6}$	0.055	$6.44x10^{1}$
Paint	192.3	4	4.1	0.93	$1.63x10^{-5}$	0.055	$2.63x10^{3}$
Brick	101.5	40	2.9	0.93	$3.30x10^{-7}$	0.055	$1.99x10^{2}$
Stone	19.4	50	2.9	0.93	$7.59x10^{-7}$	0.055	$1.09x10^{2}$
Glass	288.1	30	2.9	0.93	$3.30x10^{-9}$	0.055	4.23
							$1.26x10^{4}$

Table B-18

Calculation of D_r for r = N Ontario, $[SO_2+SO_4^{2-}]_{wet}$, 1989

$D_r = CxLxVxEx I_r x P_r$

Material	C ($x10^6$)	L	V	E'	$I'_{N\ Ont}$	$P_{N\ Ont}$	$D_{N\ Ont}$
Concrete	703.7	40	3.3	0.34	$1.28x10^{-7}$	0.055	$2.22x10^{2}$
Zinc	75.0	36	2.9	0.47	$6.43x10^{-6}$	0.055	$1.30x10^{3}$
Copper	322.1	22	3.0	0.34	$3.22x10^{-7}$	0.055	$1.28x10^{2}$
Aluminum	394.5	16	2.5	0.34	$2.68x10^{-7}$	0.055	$7.91x10^{1}$
Nickel	62.7	14	2.9	0.34	$3.19x10^{-6}$	0.055	$1.52x10^{2}$
Tin	7.6	13	2.6	0.27	$3.32x10^{-6}$	0.055	$1.27x10^{1}$
Paint	192.3	4	4.1	0.47	$6.39x10^{-6}$	0.055	$5.21x10^{2}$
Brick	101.5	40	2.9	0.47	$1.28x10^{-7}$	0.055	$3.90x10^{1}$
Stone	19.4	50	2.9	0.47	$2.94x10^{-7}$	0.055	$2.14x10^{1}$
Glass	288.1	30	2.9	0.47	$1.28x10^{-9}$	0.055	$8.29x10^{-1}$
							$2.48x10^{3}$

Table B-19

Calculation of D_r for r = Southern Ontario, $[SO_2]_{dry}$, 1989

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	I_S Ont	P_S Ont	D_S Ont
Concrete	703.7	40	3.3	0.67	$5.26x10^{-7}$	0.528	$1.73x10^4$
Zinc	75.0	36	2.9	0.93	$2.65x10^{-5}$	0.528	$1.02x10^5$
Copper	322.1	22	3.0	0.67	$1.33x10^{-6}$	0.528	$1.00x10^4$
Aluminum	394.5	16	2.5	0.67	$1.10x10^{-6}$	0.528	$6.14x10^3$
Nickel	62.7	14	2.9	0.67	$1.31x10^{-5}$	0.528	$1.18x10^4$
Tin	7.6	13	2.6	0.53	$1.37x10^{-5}$	0.528	$9.85x10^2$
Paint	192.3	4	4.1	0.93	$2.60x10^{-5}$	0.528	$4.03x10^4$
Brick	101.5	40	2.9	0.93	$5.26x10^{-7}$	0.528	$3.04x10^3$
Stone	19.4	50	2.9	0.93	$1.21x10^{-6}$	0.528	$1.67x10^3$
Glass	288.1	30	2.9	0.93	$5.26x10^{-9}$	0.528	$6.47x10^1$
							$1.93x10^5$

Table B-20

Calculation of D_r for r = Southern Ontario, $[SO_2+SO_4^{2-}]_{wet}$, 1989

$D_r = CxLxVxEx I_r x P_r$

Material	C ($x10^6$)	L	V	E'	$I'_{S\ Ont}$	$P_{S\ Ont}$	$D_{S\ Ont}$
Concrete	703.7	40	3.3	0.34	$1.98x10^{-7}$	0.528	$3.30x10^{3}$
Zinc	75.0	36	2.9	0.47	$9.95x10^{-6}$	0.528	$1.93x10^{4}$
Copper	322.1	22	3.0	0.34	$4.98x10^{-7}$	0.528	$1.90x10^{3}$
Aluminum	394.5	16	2.5	0.34	$4.15x10^{-7}$	0.528	$1.18x10^{3}$
Nickel	62.7	14	2.9	0.34	$4.94x10^{-6}$	0.528	$2.26x10^{3}$
Tin	7.6	13	2.6	0.27	$5.14x10^{-6}$	0.528	$1.88x10^{2}$
Paint	192.3	4	4.1	0.47	$9.89x10^{-6}$	0.528	$7.74x10^{3}$
Brick	101.5	40	2.9	0.47	$1.98x10^{-7}$	0.528	$5.79x10^{2}$
Stone	19.4	50	2.9	0.47	$4.55x10^{-7}$	0.528	$3.18x10^{2}$
Glass	288.1	30	2.9	0.47	$1.98x10^{-9}$	0.528	$1.23x10^{1}$
							$3.68x10^{4}$

Table B-21

Calculation of D_r for r = Lakeview, $[SO_2]_{dry}$, 1989

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{Lakeview}$	$P_{Lakeview}$	$D_{Lakeview}$
Concrete	703.7	40	3.3	0.67	$3.23x10^{-7}$	0.380	$7.64x10^{3}$
Zinc	75.0	36	2.9	0.93	$1.63x10^{-5}$	0.380	$4.51x10^{4}$
Copper	322.1	22	3.0	0.67	$8.13x10^{-7}$	0.380	$4.40x10^{3}$
Aluminum	394.5	16	2.5	0.67	$6.76x10^{-7}$	0.380	$2.72x10^{3}$
Nickel	62.7	14	2.9	0.67	$8.06x10^{-6}$	0.380	$5.22x10^{3}$
Tin	7.6	13	2.6	0.53	$8.40x10^{-6}$	0.380	$4.35x10^{2}$
Paint	192.3	4	4.1	0.93	$1.60x10^{-5}$	0.380	$1.78x10^{4}$
Brick	101.5	40	2.9	0.93	$3.23x10^{-7}$	0.380	$1.34x10^{3}$
Stone	19.4	50	2.9	0.93	$7.41x10^{-7}$	0.380	$7.37x10^{2}$
Glass	288.1	30	2.9	0.93	$3.23x10^{-9}$	0.380	$2.86x10^{1}$
							$8.54x10^{4}$

Table B-22

Calculation of D_r for r = Nanticoke, $[SO_2]_{dry}$, 1989

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{Nanticoke}$	$P_{Nanticoke}$	$D_{Nanticoke}$
Concrete	703.7	40	3.3	0.67	$1.78x10^{-6}$	0.024	$2.66x10^{3}$
Zinc	75.0	36	2.9	0.93	$8.99x10^{-5}$	0.024	$1.57x10^{4}$
Copper	322.1	22	3.0	0.67	$4.49x10^{-6}$	0.024	$1.53x10^{3}$
Aluminum	394.5	16	2.5	0.67	$3.74x10^{-6}$	0.024	$9.49x10^{2}$
Nickel	62.7	14	2.9	0.67	$4.45x10^{-5}$	0.024	$1.82x10^{3}$
Tin	7.6	13	2.6	0.53	$4.64x10^{-5}$	0.024	$1.52x10^{2}$
Paint	192.3	4	4.1	0.93	$8.82x10^{-5}$	0.024	$6.21x10^{3}$
Brick	101.5	40	2.9	0.93	$1.78x10^{-6}$	0.024	$4.68x10^{2}$
Stone	19.4	50	2.9	0.93	$4.10x10^{-6}$	0.024	$2.57x10^{2}$
Glass	288.1	30	2.9	0.93	$1.78x10^{-8}$	0.024	9.96
							$2.98x10^{4}$

Table B-23

Calculation of D_r for r = Lambton, $[SO_2]_{dry}$, 1989

$D_r = CxLxVxExI_rxP_r$

Material	C ($x10^6$)	L	V	E	$I_{Lambton}$	$P_{Lambton}$	$D_{Lambton}$
Concrete	703.7	40	3.3	0.67	$3.82x10^{-6}$	0.013	$3.09x10^{3}$
Zinc	75.0	36	2.9	0.93	$1.93x10^{-4}$	0.013	$1.82x10^{4}$
Copper	322.1	22	3.0	0.67	$9.63x10^{-6}$	0.013	$1.78x10^{3}$
Aluminum	394.5	16	2.5	0.67	$8.01x10^{-6}$	0.013	$1.10x10^{3}$
Nickel	62.7	14	2.9	0.67	$9.54x10^{-5}$	0.013	$2.12x10^{3}$
Tin	7.6	13	2.6	0.53	$9.95x10^{-5}$	0.013	$1.76x10^{2}$
Paint	192.3	4	4.1	0.93	$1.89x10^{-4}$	0.013	$7.21x10^{3}$
Brick	101.5	40	2.9	0.93	$3.82x10^{-6}$	0.013	$5.44x10^{2}$
Stone	19.4	50	2.9	0.93	$8.78x10^{-6}$	0.013	$2.99x10^{2}$
Glass	288.1	30	2.9	0.93	$3.82x10^{-8}$	0.013	$1.16x10^{1}$
							$3.45x10^{4}$

Table B-24

Social Costs (1989)

Region (r)	Pollutant	D_r ($)
Northern Ontario	SO_2 (dry)	1.26×10^4
	$SO_2 + SO_4^{2-}$ (wet)	2.48×10^3
Southern Ontario	SO_2 (dry)	1.93×10^5
	$SO_2 + SO_4^{2-}$ (wet)	3.68×10^4
Lakeview	SO_2 (dry)	8.54×10^4
Nanticoke	SO_2 (dry)	2.98×10^4
Lambton	SO_2 (dry)	3.45×10^4
		3.95×10^5

Fossil-fuel generated electricity to be exported = 5585 GWh

= 5.59×10^9 kWh

$$\therefore \text{Social Costs} = \frac{\$3.95 \times 10^5}{5.59 \times 10^9 \text{ kWh}}$$

= 0.07 mills/kWh

APPENDIX C

SO_2/SO_4^{2-} CONCENTRATION AND DEPOSITION DATA

The data listed in the following tables was provided by Central Thermal Services and the Atmospheric Research Section.

TABLE C-1

SO_2 DRY DEPOSITION DATA

Region	Year	$[SO_2]$ All Sources ppb ($\mu g\ m^{-3}$)	% Contribution due to Ontario Hydro Exports	$[SO_2]$ Ontario Hydro Exports ppb ($\mu g\ m^{-3}$)
Lakeview	1982	5.2	3.2	0.17 (4.45×10^{-1})
Lakeview	1986	4.9	0.5	0.03 (6.42×10^{-2})
Lakeview	1989	4.8	0.3	0.02 (3.80×10^{-2})
Nanticoke	1982	5.2	4.3	0.22 (5.86×10^{-1})
Nanticoke	1986	4.9	2.8	0.14 (3.60×10^{-1})
Nanticoke	1989	4.7	1.7	0.08 (2.09×10^{-1})
Lambton	1982	8.5	9.6	0.82 (2.13)
Lambton	1986	7.3	4.4	0.32 (8.42×10^{-1})
Lambton	1989	6.8	2.5	0.17 (4.45×10^{-1})
Algoma	1982	1.32 (3.47)	1	1.32×10^{-2} (3.47×10^{-2})
Algoma	1986	1.48 (3.89)	1	1.48×10^{-2} (3.89×10^{-2})
Algoma	1989	1.48 (3.89)	1	1.48×10^{-2} (3.89×10^{-2})
Muskoka-Haliburton	1982	2.08 (5.47)	2	4.18×10^{-2} (1.09×10^{-1})
Muskoka-Haliburton	1986	2.39 (6.27)	1	2.39×10^{-2} (6.27×10^{-2})
Muskoka-Haliburton	1989	2.37 (6.20)	1	2.37×10^{-2} (6.20×10^{-2})

TABLE C-2

$SO_2+SO_4^{2-}$ WET DEPOSITION DATA

Region	Year	$[SO_2+SO_4^{2-}]$ All Sources SO_4^{2-} µg m^{-3} [a] (SO_2 µg m^{-3})	% Contribution Due to Ontario Hydro Exports	$[SO_2+SO_4^{2-}]$ Ontario Hydro Exports SO_4^{2-} µg m^{-3} (SO_2 µg m^{-3})
Algoma	1982	1.41 (3.36)	1	1.41×10^{-2} (3.36×10^{-2})
Algoma	1986*	1.62 (3.79)	1	1.62×10^{-2} (3.79×10^{-2})
Algoma	1989*	1.61 (3.76)	1	1.61×10^{-2} (3.76×10^{-2})
Muskoka-Haliburton	1982	2.17 (5.17)	2	4.34×10^{-2} (1.03×10^{-1})
Muskoka-Haliburton	1986*	2.51 (5.86)	1	2.51×10^{-2} (5.86×10^{-2})
Muskoka-Haliburton	1989*	2.49 (5.82)	1	2.49×10^{-2} (5.82×10^{-2})

*Projections for 1986 and 1989 based on 1981 deposition data.

[a]Data originally obtained in units of g SO_4^{2-} m^{-2}.